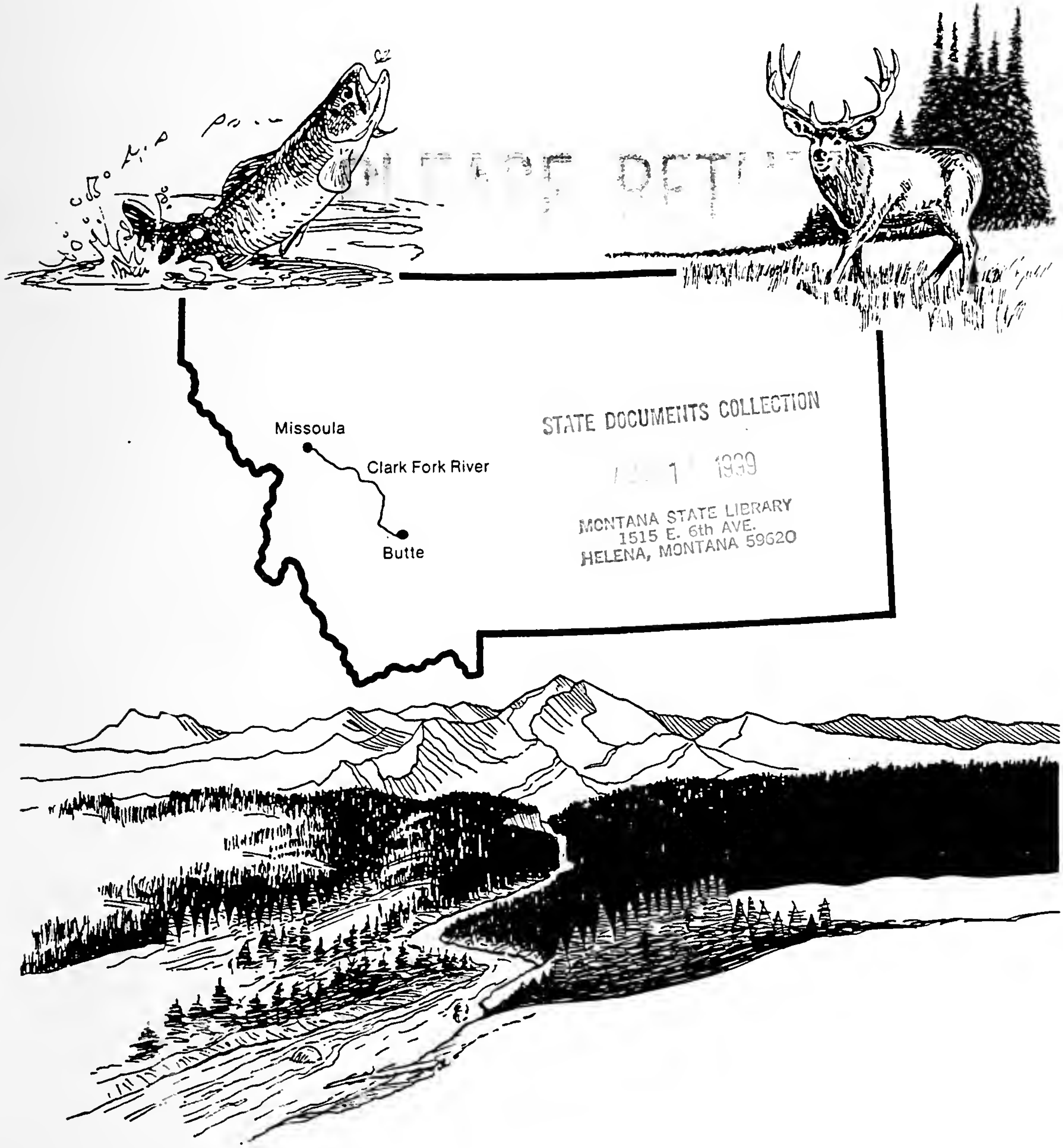
STATE OF MONTANA
NATURAL RESOURCE DAMAGE PROGRAM

EVALUATION AND CRITIQUE OF THE STREAMBANK TAILINGS AND REVEGETATION STUDIES (STARS) REMEDIATION TECHNOLOGY

OCTOBER 1995



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PREPARED FOR
STATE OF MONTANA
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INDIVIDUAL REPORTS PREPARED BY:

(1) SUMMARY BY MARK KERR

(2) DR. ANN S. MAEST

(3) DR. LAWRENCE A. KAPUSTKA

(4) DR. JIM GANNON

(5) DR. STANLEY SCHUMM

(6) DR. EUGENE FARMER

SUMMARY OF

EVALUATION AND CRITIQUE OF THE STREAMBANK TAILINGS AND REVEGETATION STUDIES (STARS) REMEDIATION TECHNOLOGY

OCTOBER 1995

Mark Kerr

MARK KERR
STATE OF MONTANA
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STARS REPORT - SUMMARY

INTRODUCTION

This report is submitted in rebuttal to ARCO's expert reports concerning the efficacy of STARS (reports provided by Drs. Redente, Davis and Ginn). In responding to ARCO's reports, this report also presents the State of Montana, Natural Resource Damage Litigation Program (Montana) analysis of the STARS (Streambank Tailings and Revegetation Studies) *in-situ* tailings remediation technology and comments upon the utilization of STARS as a remedial technology for floodplain tailings.

The objective of the STARS studies was to evaluate a potential *in-situ* remediation technology that would provide a degree of protectiveness to surface water and groundwater, in terms of immobilizing tailings contaminants (primarily the metals cadmium, copper, lead and zinc, and the metalloid arsenic) that pose threats to human health and the environment.

STARS research proceeded through three phases. Phase I tested a variety of chemical amendments on tailings in the laboratory to determine the best combination of amendments that reduced the concentration of metals measured in water leached through amended tailings. Greenhouse studies were also undertaken to determine the best mixture of plant species that would grow in amended tailings. Phase II consisted of field trials to test the most effective chemical amendments determined in Phase I. Phase III consisted of collecting various types of soil, water, and vegetative data over the course of three years and evaluating each of the treatments applied (MDEQ, 1995).

Further testing of STARS occurred in the early 1990s, when three demonstration projects were implemented along Silver Bow Creek to field test STARS techniques on a larger scale than had been done to date. In addition, the State in 1990 utilized STARS techniques on a tailings treatment project along a reach of the upper Clark Fork River. Known as the "Governor's Project," tailings extending approximately one and one-half miles downstream of the Warm Springs Ponds were lime-amended after contaminated runoff from tailings resulted in a fishkill in 1988. The Governor's Project was an attempt to alleviate conditions conducive to storm-event runoff and fishkills. Results-to-date from the demonstration projects and the Governor's Project are often cited by the Atlantic Richfield Company (ARCO) as proof of the viability of STARS,

and its utility as a remediation technology for floodplain tailings along Silver Bow Creek (and by extrapolation, the Clark Fork River).

At the present time, a Record of Decision (ROD) is being prepared for the Streamside Tailings Operable Unit (SSTOU), which is generally contiguous with Silver Bow Creek and its floodplain. The ROD, which will identify the selected remedy for Silver Bow Creek, is expected to be finalized shortly. Based on Superfund's Proposed Plan for Silver Bow Creek and the position of ARCO, it is probable that STARS will be a significant component of the selected remedy. Based on analyses of the authors of this report, it is expected that the widespread application of STARS to floodplain tailings will, in time, fail.

While many issues can be identified and discussed relative to the STARS technology, the following discussion will focus on two key issues: The long-term neutralization success of lime-amended tailings, and the long-term success of revegetation. Failure to accomplish either of these objectives will render a remedy with a significant STARS component essentially useless over time.

This report includes five reports and this summary authored by Montana experts that discuss various issues related to STARS. These discussions are based on review of STARS reports produced under Superfund investigations; independent study on issues related to STARS; and review and critique of ARCO reports submitted to Montana as part of the lawsuit Montana v. ARCO. The five Montana reports included herewith are as follows:

- Dr. Ann Maest (Hagler Bailly): *Rebuttal of ARCO's Reports on STARS.* Dr. Maest reviews and critiques work conducted on behalf of ARCO by Dr. Andy Davis. Dr. Davis' work involved numerous geochemical studies and investigations related to amended and unamended floodplain tailings.

- Dr. Larry Kapustka (ecological planning & toxicology, inc.): *Rebuttal of ARCO's Reports on STARS.* Dr. Kapustka reviews and critiques work conducted on behalf of ARCO by Dr. Edmund Redente. Dr. Redente's work involved microbiological and soil studies of amended and unamended floodplain tailings. Dr. Kapustka also presents information related to the long-term success of tailings revegetation, including arsenic phytotoxicity; metals availability and nutrient cycling; and soil salinity and plant osmosis.

■ Dr. Jim Gannon (University of Montana): *Comments on the Impact of STARS Reclamation Technology on Bacterial Pyrite Oxidation and Other Microbial Mechanisms Important in Metal Mobilization* and *Comments on the Expert Report of Edward F. Redente: Carbon Accumulation, Biomass, and Microbial Numbers in Tailings.* Dr. Gannon discusses results of his research on microbial processes within floodplain tailings, in the context of STARS. Dr. Gannon also reviews and critiques work conducted on behalf of ARCO by Dr. Edmund Redente.

■ Dr. Stan Schumm (Owen Ayres & Associates, Inc.): *Channel Change. Silver Bow Creek and Clark Fork River.* Dr. Schumm discusses his analysis of channel change in Silver Bow Creek and the Clark Fork River, and implications to STARS-treated floodplain areas.

■ Dr. Eugene Farmer (Farmer and Associates, L.L.C): *Comments on ARCO's Reports Concerning the Revegetation of Acid Tailings near Cooke City, MT; the Idarado Mine, CO; and on Whitewood Creek, SD.* Dr. Farmer discusses reclamation efforts at other locations cited by ARCO as examples of successful revegetation efforts.

This summary was prepared by Mark Kerr of Montana's Natural Resource Damage Litigation Program. This summarizes and integrates information presented in the five reports and discusses the following questions:

1. Did the STARS studies generate reliable data?
2. Can tailings be effectively neutralized over the long-term?
3. Can a vegetative cover be effectively maintained over the long-term?
4. Will STARS treatment be successful over the long-term?
5. Is STARS an appropriate remediation technology to prevent erosion of tailings?
6. Does ARCO provide any evidence or information to support a conclusion that STARS is a proven, effective long-term remediation technology?

Did the STARS studies generate reliable data?

Fundamental to any discussion about the long-term success of STARS is the quality and usefulness of data generated by the various STARS studies. In their review of STARS reports, Montana's experts have identified deficiencies in the design of STARS studies and in the collection and analysis of data from lime-treated tailings plots. These deficiencies create considerable uncertainty regarding conclusions that STARS is an effective, long-term remediation technology. Some of the problems identified in the study design and data collection aspects of STARS are the following:

1) The degree of heterogeneity in tailings and associated pore fluids confounds interpretations concerning the effects of various treatments. The study was designed using control and test plots from which data were collected to assess the benefits of lime-amendments. Because of the lateral and vertical heterogeneity of floodplain tailings, improvements discerned by comparing effects in treated plots to control plots cannot be attributed to the amendments (that is, characteristics of control plots may be very different from conditions in treatment plots). To illustrate, Shafer (1993) concluded that "due to natural variability of flood-deposited tailings and the variable amendment incorporation at depth, marked differences in pore water chemistry could not be attributed to the primary treatments."

2) The selection of control plots. No control plots were established on undisturbed tailings. All control plots were plowed to a shallow depth, thus disturbing existing biogeochemical conditions within the tailings profile. This makes it impossible to discern effects of amendments from effects of other biological, hydrological, and chemical processes that occur in undisturbed floodplain tailings.

3) Compositing of samples from different depths (for example, 0-8 cm fraction with the 8-15cm fraction) diminishes the ability to discern small scale trends in water soluble metals concentrations that may have aided in data interpretation. Sample compositing intervals were also not consistent with amendment depths, thus confounding interpretations related to the effectiveness of amendments. (See NRDLP, 1994).

These are just a few examples of how experimental design and data collection raise questions concerning the reliability and interpretations of the efficacy of STARS.

Can tailings be effectively neutralized over the long-term?

STARS involves *"chemically neutralizing and fixing contaminants by incorporation of soil amendments into mine waste and revegetating with acid or metal-tolerant grass species"* (Schafer et al., 1993). Soil amendments were specified to reduce the mobility and bioavailability of <u>most</u> contaminants, and vegetation cover would <u>reduce</u> the quantity and improve the quality of surface runoff and leachate passing through waste materials (Schafer et al., 1993). Soil amendments include combinations of limestone, hydrated lime, ferric sulfate and phosphogypsum. Hydrated lime and limestone are key amendments because they are necessary to neutralize acidity and potential acid generation within tailings. The primary chemical reaction in streambank tailings that affects contaminant mobility is acidification by oxidation of sulfide minerals (especially pyrite), and by hydrolysis of ferric iron to form ferric hydroxide. Both of these reactions create acids. In general, the solubility of metals increases as pH decreases (the mobility of arsenic in soils tends to increase as pH increases). Once contaminants are soluble, they are more readily mobilized by release mechanisms and transported out of the tailings (Schafer et al., 1993).

Successful implementation of STARS requires correct calculation of the amount of lime to completely and indefinitely neutralize acidity and the acid-generation potential of floodplain tailings. STARS also requires successful incorporation (i.e. mixing) of lime and other amendments into tailings. The calculated lime requirement is based on an acid-base potential analysis of various tailings samples that accounts for the active acid-generating potential of tailings, acid soluble forms of sulfur capable of generating acid, and the inherent neutralization potential of tailings/soils (EA ES&T, 1992). Theoretically, the amount of lime required would completely address the <u>active</u> and <u>potential</u> acid generation of the tailings of interest, neutralizing the tailings forever.

The assumptions underlying the theoretical basis of STARS are, at best, questionable and unconvincing. First, it is assumed that lime amended into tailings is completely available for neutralizing existing and potential acidity <u>forever</u>. Second, it is assumed that amendments can be completely mixed into the tailings at a macro- and microscale that is relevant to the establishment of vegetative cover. Third, it is assumed that no secondary weathering products are created that increase the solubility and mobility of metals. Finally, it is assumed that

geochemical conditions resulting from liming are not conducive to microbial processes that generate acid and mobilize metals.

Lime Availability for long-term neutralization of acid-generating capacity

To ensure the long-term availability of acid-neutralizing capacity, amendments must remain physically accessible. That is, physical and/or chemical alterations of lime amendments cannot occur that would render them inaccessible to acid generated in amended tailings. Amendments that are too coarse may be coated by precipitates, usually iron hydroxide ($Fe(OH)_3$) that may limit the availability of neutralizing capacity. Dissolution of the ferric sulfate and phosphogypsum amendments will also add to the armoring of lime particles. When dissolved, both will release sulfate, which will precipitate on the surface of limestone as calcium sulfate. This physical/chemical alteration can be described most simply as "armoring" of lime amendments (NRDLP, 1994). Such armoring renders amendments inaccessible to acid generated in tailings.

Amendment mixing

To ensure long-term vegetative success, lime amendments must be mixed into tailings so as to create a homogeneous soil with respect to acidic and limed pockets. MDEQ (1995) recognizes that the neutralizing amendment must be in intimate contact with the acid material if it is to effectively neutralize generated acid. To be effective, the scale of interest is the volume occupied by roots and their associated microflora (i.e. between less than a cubic millimeter and a cubic centimeter). As root growth penetrates into unfavorable soil conditions, including acidic pockets or toxic zones, the associative bacteria do poorly. In turn, the root also does poorly, to the point of die-back. In addition, plant roots commonly exude protons, resulting in a slight acidification of the rhizosphere. The interaction of plants and the physico-chemical processes that promote acid generation pose serious concerns regarding the long-term effectiveness of lime additions. Whenever the neutralization balance is lost, even on a micro-habitat scale, nutrient availability for plant growth will decline. (See Kapustka, 1995).

From observations and analyses of plant rooting in STARS plots, plant roots in poorly mixed soils tended to avoid acidic pockets and, instead, exploited areas where liming had

mitigated acidic soil conditions. Root growth in lime-treated acid soils would be restricted to neutralized "pockets" and excluded from poorly mixed zones. This results in added interference among plants, reducing productivity and increasing erosion (Kapustka, 1995).

Amendment mixing at the microscale is also relevant to the microbial processes which occur in tailings and which can affect acid generation in tailings. Given that complete amendment mixing is difficult even at the macroscale, it is not difficult to imagine many micrometer to millimeter areas where amendment mixing is incomplete and amendments are not accessible. These will constitute regions of greater acid-generation by microbial processes such as pyrite oxidation and reduction of metal oxides. (See Gannon, 1995).

Creation of Secondary Weathering Products

Tailings contain a number of secondary weathering products formed by the oxidation of sulfides. Samples collected from the Governor's Project contained iron/manganese oxyhydroxides containing arsenic, copper, lead and zinc, and jarosite containing lead, arsenic and copper. Davis (1995) concluded that precipitation of secondary minerals, including jarosite and other iron sulfate minerals, removes metals from solution. According to Maest (1995), however, jarosite and other iron sulfate minerals are very soluble. The lead, arsenic, and copper associated with jarosite will be released to the interstitial water when that portion of the soil profile becomes saturated (or it may be present in the soil water in the saturated zone). Maest concluded that *"at least some of the secondary minerals in tailings and soils will actually increase the mobility of contaminants in the streamside tailings over what the mobility would have been before the secondary minerals were formed."* Maest (1995) also noted that *"at higher pH values, jarosite is more soluble, so amendment of tailings, that have weathered and formed jarosite would tend to generate high concentrations of metals, especially of those metals associated with the precipitated jarosite."* Maest further notes that the association of arsenic with jarosite may partially explain why higher pH values in amended tailings are associated with higher arsenic concentrations. Solubility of jarosite, which would result in higher soil solution concentrations of arsenic, could be a factor in the increased phytotoxicity of arsenic at higher pHs.

Microbial Processes in Amended Tailings

Microbial processes that occur in tailings were not investigated in the STARS studies. Microbial processes that generate acid occur in tailings, including pyrite oxidation and reduction of metal oxides. One objective of STARS is to neutralize acid generated by these processes through the incorporation of lime. In lime-amended zones, an increase in pH will decrease the activity of acidophilic iron-oxiding bacteria and diminish acid generation. However, even in lime-amended tailings where pH levels increase due to the neutralization of acidity through lime incorporation, a number of different microbial processes occur that generate acid. Iron- and sulfur-oxidizing bacteria, as a functional group, remain capable of acid generation over a broad pH range (Gannon, 1995). In addition, Gannon found that both acidophilic iron-oxiding bacteria and neutrophilic sulfur-oxidizing bacteria are widely distributed in an unamended tailings site across a broad range of pH conditions. This indicates that under a variety of pH conditions microbial populations capable of acid generation will continue to be active in the tailings profile. Gannon states that liming will not eliminate acid-generation by all microbial processes because these processes will occur even under neutral pH conditions resulting from lime incorporation. Gannon concluded: *"in amended zones neutralization and vegetation will decrease but not eliminate microbial acid-generation."*

Can a vegetative cover be successfully maintained over the long-term?

The long-term success of STARS depends upon the successful establishment of a vegetative cover on floodplain tailings. The vegetative cover is necessary to break contaminant migration pathways, such as the infiltration of precipitation (and associated contaminants) to groundwater and surface runoff (and associated contaminants) to surface water. The establishment of a vegetative cover depends on successful neutralization of tailings' acidity. An increase in tailings pH reduces the bioavailability of metals to plants. The plants, in turn, utilize soil moisture that would otherwise infiltrate to groundwater, and provide soil cover and structure that reduces runoff of precipitation to surface water. The long-term success of STARS depends on maintaining a vegetative cover permanently.

Unfortunately, limitations associated with STARS virtually guarantees that any vegetative

cover established in the short-term will not last indefinitely. From the preceding discussion, it is clear that liming will not completely and indefinitely eliminate acid generation within tailings. Physical limitations prevent mixing at either a macroscale or microscale to homogeneously incorporate amendments into tailings. Where physical incorporation of lime is complete and increases pH levels, secondary weathering products formed by the oxidation of pyrite, such as jarosite, become more soluble. In both neutralized (amended) and acidic (unamended) tailings, microbial processes occur that lead to acid generation and solubilization of hazardous substances. The processes of acid generation and solubilization of hazardous substances will adversely affect plant performance. In addition, as described below, soil conditions created in amended tailings are not favorable for sustained plant growth.

Three issues directly affect plant performance and vegetative success: Arsenic phytotoxicity; metals bioavailability and nutrient cycling; and soil salinity/osmotic stress. Arsenic phytotoxicity is important because lime amendments will increase the bioavailability of arsenic. Adequate nutrient cycling for plant performance relies on neutralization balance, that is, soil conditions that are neither too acid or to alkaline. Finally, the addition of lime to sandy soils increases salinity, making it more difficult for plants to obtain water. (See Kapustka, 1995).

Although arsenic solubility is partially lowered by calcium, light textured tailings soils with high arsenic concentrations will continue to pose phytotoxic risk to plants. The availability of arsenic to plants and the potential for plant toxicity depends on many factors, including soil pH, texture, fertility level, and plant species. To be absorbed by plants, arsenic compounds must be mobile in the soil solution. An increase in pH leads to higher soil solution concentrations of arsenic (Kapustka, 1995). Maest (1995), as previously discussed, notes that the association of arsenic with jarosite, and the increased solubility of jarosite at higher pHs, may partially explain why higher pH values in amended tailings are associated with higher arsenic concentrations. For most plants, significant depressions in crop yields are evident at soil arsenic concentrations of 3 to 28 mg/l of water soluble arsenic and 25 to 85 mg/l of total arsenic. A soil concentration as low as 2 mg/l soluble arsenic is considered the threshold level for marked damage to alfalfa and barley, whereas 3.4 to 9.5 mg/l soluble arsenic causes "poor condition" of young seedlings. These phytotoxic thresholds are all substantially less than concentrations observed in lime-amended tailings (Shafer et. al, 1993). It is likely that arsenic

phytotoxicity will occur to some degree in the long run.

Nutrient cycling is intimately dependent on soil microorganisms. As soil pH approaches neutrality, a broad spectrum of soil bacteria become active. Plants benefit from bacterial metabolism that ward off pathogens, mineralize essential nutrients, and buffer the soil zone surrounding roots. As root growth penetrates into unfavorable soil conditions, including acidic pockets or toxic zones, the associative bacteria do poorly. In turn, the root also does poorly to the point of die-back. Plant roots commonly exude protons resulting in a slight acidification of the rhizosphere. Whenever the neutralization balance is lost (even on a microhabitat scale), nutrient availability for plant growth will decline. Negative plant yield responses to liming often occur on strongly acid, leached soils of temperate areas. Furthermore, it was found that liming can cause acidification of the subsoil and the displacement of heavy metal ions. Liming appears to stimulate fine root development in the uppermost soil layers, increasing the danger of frost and drought damage.

Finally, the addition of lime to sandy soils results in sharp increases in salinity. The ability of a plant to acquire water from soil is related to its ability to maintain a lower water potential than their surrounding medium. Salinity lowers the water potential of soil water, making it more difficult for plants to obtain water. As soil water decreases during dry periods, the salt content of the pore water will increase. If sufficient soluble salt is available, the water will achieve osmotic levels that preclude uptake by many plants, and subsequent stoppage of photosynthesis. This sequence of events is prone to limit the competitive capability of sensitive plants. Ionic effects also reduce the ability of plants to harden (i.e. withstand low and freezing temperatures).

In summary, amendments incorporated into tailings to neutralize acidity and immobilizing metals create conditions unfavorable to the long-term maintenance of vegetation. (Also see Dr. Eugene Farmer's *"Comments on Proposed Plan: Streamside Tailings Operable Unit,"* August 2, 1995, Attachment A, hereto.)

Will STARS treatment be successful over the long-term?

Numerous limitations have been identified in the STARS technology which, when

considered together, leads to the conclusion that STARS will not be successful in the long-term. First, there is no evidence that adequate and effective mixing of amendments into deeper tailings can be achieved. For example, data from the STARS studies demonstrated adequate and effective amendment incorporation only to depths of about 6 inches. No data were presented that could led one to conclude with a reasonable degree of assurance that mixing at greater depths was adequate and effective (NRDLP, 1994). Second, as noted in the discussion above, mixing must be so thorough so as to create essentially a homogeneous soil with respect to acidic and limed pockets. To be effective, the scale of interest is the volume occupied by roots and their associated microflora (i.e. between $< mm^3$ and cm^3) and the scale at which microbial processes related to acid generation and metals solubilization occurs. At the scale of interest, adequate and effective mixing of lime is difficult if not impossible.

Third, the amending of lime into tailings creates conditions that can adversely affect plant performance and can increase acid generation and metals solubilization. Maest (1995) concluded that some secondary weathering products formed in lime-amended soils may actually be more soluble than those in unamended soils, and may increase the acid-generation potential of soils. Gannon (1995) describes microbial processes that occur in neutral tailings that result in acid generation and metals solubilization. Kapustka (1995) discusses the increased arsenic toxicity in lime-amended soils, together with soil conditions (i.e. soil salinity) that will not be amenable to the long-term sustenance of vegetation. Taken together, this leads to the conclusion that STARS is not a permanent fix for immobilizing hazardous substances in floodplain tailings. The information provided by Montana's experts indicates, with a reasonable degree of certainty, that over the long-term the STARS treatment proposed for remediation will fail to a significant degree.

Is STARS an appropriate remediation technology to prevent erosion of tailings?

Criteria defining where STARS may be effectively and reliably implemented are set forth in the proposed remediation plan for streamside tailings (MDEQ, 1995). These criteria include locations where tailings/impacted soils may not be eroded and reentrained into the stream through normal stream processes or major flood events. Based on these criteria, STARS is proposed to be utilized across an estimated 160 acres outside the 100-year floodplain in Subarea

II (generally Ramsay Flats) and over about 400 acres in Subarea IV (below Durant Canyon) inside the 100-year floodplain. Utilization of STARS may be inconsistent with these criteria.

Many areas along Silver Bow Creek are susceptible to erosion and reentrainment of tailings. For example, Schumm (1995) notes that in Subarea II the increase in channel sinuosity between 1955 and 1990 may be an indication that instead of the avulsive change which has occurred over this area in the past, the channel will develop a more sinuous course with bank erosion the primary mode of channel change. Thus it only can be concluded that STARS-treated tailings at Ramsay Flats in Subarea II will erode to Silver Bow Creek. Schumm also states that the many abandoned channels in the reach downstream of Durant Canyon (Subarea IV) are evidence of frequent avulsion (i.e. sudden channel shift) in the past. Future avulsion and meander to almost any location in this reach can be expected, despite local channel confinement and straightening. Schumm concludes that "Silver Bow Creek will erode tailings, as the channel wanders across its valley floor, develops meanders or when it avulses across tailings." Therefore, the low probability that STARS can maintain a permanent vegetative cover, together with the certainty of erosion along many areas of Silver Bow Creek, argues for the removal of tailings/impacted soils along Silver Bow Creek.[1] Moreover, most of the tailings areas along the creek do not satisfy the erosion criteria for utilization of STARS set forth in the proposed remediation plan. (Also see letter from Glenn Phillips on this issue, Attachment C, hereto.)

Does ARCO provide any evidence or information to support a conclusion that STARS is a proven, effective long-term remediation technology?

Given the "weight of evidence" against the long-term success of STARS, ARCO's "evidence" of the long-term sustainability of STARS technology in reclaiming streamside tailings

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[1] Dr. Frank Munshower, in a letter to Mr. Glenn Phillips of the Montana Department of Fish, Wildlife and Parks (dated February 22, 1995) acknowledges the inappropriateness of using STARS in a meandering stream system. (Attachment B, hereto.) Dr. Munshower states "This technology [STARS] is not appropriate when tailings are in a location that will be subjected to erosion by a meandering stream in the near future." It should be noted that Dr. Munshower, of the Montana State University Reclamation Research Unit, was a key investigator in the development of the STARS technology.

is weak and easily refuted. Redente (1995) studied amended and unamended tailings collected from the Governor's Project. While some data were collected by Redente (i.e. soil organic matter, nitrogen levels, microbial numbers and biomass), deficiencies in the study design undermine his conclusions concerning the efficacy of STARS. For example, the study lacked an appropriate control of unamended tailings that is necessary to draw conclusions concerning the beneficial effects of lime amendments on tailings. As another example, Redente's one-time, static measure of carbon and other soil indices cannot support conclusions concerning trends in soils improvements.

Gannon (1995) also notes that Redente's comparisons and analyses of the microbiological community are very simplistic. For example, fungal to bacterial ratio's used by Redente are *"at best a very, very gross measure of community structure...[and the] ratios say very little about the functioning of the system"*. Indeed, Gannon concludes that many of the measures of improvement cited by Redente are quite comparable to levels measured by Gannon in unamended tailings along Silver Bow Creek.

Finally, Dr. Redente's conclusion that *"measures of fertility and microbial populations in the Governor's Project area are within a range to be expected for a newly developing plant community"* speak in no way to the long-term sustainability of a vegetative cover. According to Kapustka (1995), *"his work does not address the fundamental outstanding issues raised concerning the permanence of STARS vis-a-vis toxicity and nutrient conditions."*

Dr. Redente's opinions are based, in part, upon the work done by Davis (1995) for ARCO. As discussed by Maest (1995) above, Dr. Davis evaluated the long-term stability issue by analyzing amended and unamended tailings for bulk metals concentrations; mineralogical analyses; humidity cell tests; pore water chemistry; and geochemical modeling of attenuation. In general, Dr. Davis' opinion that *"these data indicate that the remediation is effective in the long-term"* is highly suspect. Maest identifies numerous problems in analytical methods used, data interpretation, and sampling design. For example, contrary to Dr. Davis' opinion that secondary weathering products "have removed metals from solution in the natural weathering environment, greatly reducing their potential for leaching through the soil profile," Maest concludes that *"at least some of the secondary minerals found in the tailings and soils horizons will actually increase the mobility of contaminants in streamside tailings."* Similarly, Dr. Davis'

conclusion regarding results of humidity cell tests, that "lime amendments have increased neutralization capacities and increased soil pH, resulting in long-term geochemical stability", is very narrow. In fact, Dr. Davis' own data (not reported in his Expert Report) show that *"a substantial amount of copper is leaching from the amended 12-15 inch depth and from the buried A horizon sample (15-20 inches)"* (Maest, 1995). This finding also contradicts Dr. Ginn's opinion that *"Results of humidity cell tests...indicate that a STARS amendment will be effective in the long-run."* Regarding Dr. Davis' soil-leaching and metal-partitioning experiments, Maest questions the methodology used, stating that *"the high application rate of water essentially assures that the leach rate will decrease with time"*, and *"the experimental design of the metal partitioning experiments is so questionable that the results cannot be considered meaningful."*

Ginn (1995) cites to demonstration projects on Silver Bow Creek, the Governor' Project, and projects in other locales as evidence of the long-term viability of STARS. He states, for example, that "the preponderance of evidence at demonstration projects I and II indicates that the amendment is present at levels sufficient to neutralize acid generating capacity of sulfide." Similarly, Ginn states that: "Additional evidence supporting the long-term effectiveness of STARS techniques is provided by long-term results at other mining sites. For example, revegetation of mine tailings at a site near Cooke City, Montana has thrived for more than 17 years. Similar success has been demonstrated at mining Superfund sites in Whitewood, South Dakota and the Idarado site in Colorado."

As discussed by Farmer (1995), Ginn's conclusions are misleading. The sites alluded to by Ginn near Cooke City, Whitewood and Idarado are inappropriate as comparisons for Silver Bow Creek for a number of reasons, including site geology, types of mining wastes, and the nature and intensity of revegetation efforts. The two sites reviewed by Farmer near Cooke City reveal either no successful revegetation, or successful revegetation but on overburden waste which is very different from the streamside tailings along Silver Bow Creek. At Whitewood, the degree to which vegetation has reestablished <u>naturally</u> without human intervention speaks to differences between the sites. The similarity of success at Idarado is very questionable, as reclamation efforts there have occurred only over the last few years.

Demonstration projects along Silver Bow Creek would also seem to provide little support for Dr. Ginn's conclusions. In January, 1995 the Montana State University Reclamation

Research Unit (MSU RRU), which conducted much of the STARS research, provided a critique of demonstration projects I, II and III (MSU RRU, 1995a; 1995b; 1995c). These critiques provide much evidence which is contrary to Dr. Ginn's opinion.

At Demonstration Project I, MSU RRU found that implementation of the project was fraught with errors. The following statements are taken from the MSU RRU memorandum to Superfund:

- "The accumulated effect of these errors [i.e. assumptions underlying the lime application rate] indicates repository KD [that is, lime kiln dust] applications may have been too low by a factor of approximately 65%. The quantity of KD applied would be sufficient to neutralize active acidity presently in the system, but reacidification in the future is likely."
- "Samples were collected from two pits in area S2 and one pit from area N2...Treatment of these tailings with lime was a complete failure...Lime application failed to adjust the pH level to one suitable for plant growth. In addition, the measured pH over time indicates that either the site is reacidifying or field sample collection procedures are not representative."
- "In are N2...data indicate site reacidification is occurring or sample collection is not representative...Lime incorporation efforts were not successful."
- "...ARCO/Titan are misinterpreting acid-base potential (ABP) data presented in Figure 17-21...This result indicates these materials will reacidify in the future, i.e. they are <u>not</u> adequately neutralized..."
- "Tailings were deposited approximately 5 ft. thick and the top 2 feet were limed [at the N1 tailings repository]

  ...At location N1, the ABP...indicates acidic conditions will prevail in the future."
- "ARCO needs to study their data in greater depth and determine why lime treatment failed to neutralize materials planned for remediation. Treatment associated with Option 3 was not successful."
- "Lime was plowed 4 feet into tailings which were left in place in the flood plain...neutralization of these tailings was incomplete."

MSU RRU concluded, in summary, that: "In localized areas plant performance was poor or nonexistent. Samples collected in these "bare areas" indicated that soil pH was often too low for good plant growth...Data presented in the Project I report and these field observations indicate lime application rates may have been insufficient. It is very apparent that applied lime was not uniformly incorporated in the profile to the target depth...lack of initial sampling and analysis of tailings, inappropriate logic used in designing lime application rates, poor amendment incorporation have resulted in incomplete site neutralization."

At Demonstration Project II, MSU RRU found similar errors that compromised the viability of the project. The following statements are taken from the MSU RRU memorandum to Superfund:

- "...ARCO used inappropriate logic in developing lime application rates for Demonstration Area II. The error is a serious one and should not be made in future project work."
- "ARCO indicates the site soil pH ranged from 5.85 to 7.48 prior to seeding...Soil pH levels of 5.8 indicate lime application/incorporation was ineffective."
- "There is little data to support any conclusion of groundwater quality improvements."

At Demonstration Project III, MSU RRU found similar errors that compromised the viability of the project. The following statements are taken from the MSU RRU memorandum to Superfund:

- "ARCO indicates surface soil pH ranged from 5.41 to 7.19, but fails to indicate sampling depth, sample number and sample distribution on a map. If most of the area has pH levels less than 6, then remediation efforts were a failure."
- "ARCO concludes amendment incorporation was "...acceptable, but not homogeneous...Variations of up to 1.5 pH units were seen in the mixed zone.

However, these pHs were all above the 6.5 standard units." This statement is both incorrect and false. Pictures in Appendix C reveal a pH range of approximately 3.5 to 8.0 in these soil profiles."

- "There is little data to support any conclusion of groundwater quality improvements."

CONCLUSION

In summary, a review and analysis of the accompanying reports and issues relating to the STARS remediation technology leads to the conclusion that STARS will not be viable over the long-term. (Also see Dr. Farmer's analysis in Attachment A, hereto.) Neutralization of tailings, and the vegetative growth that depends on long-term neutralization of tailings, will fail over time. Moreover, the STARS treated tailings will inevitably erode. This makes STARS unsuitable as a remediation technology. This conclusion is supported by the following summary points:

- Mixing of amendments and tailings, at a macroscale, is incomplete. Pockets of acidity and acid-generating tailings will remain and be phytotoxic to vegetation.
- At a microscale important to plant rooting, incomplete amendment mixing will enable acidic and toxic conditions to plant roots to exist, and will impair the cycling of nutrients necessary to sustain vegetation.
- In both amended (neutralized) and unamended (acidic) tailings, microbial processes that generate acid and increase the bioavailability of metals to plants will occur.
- Increases in pH related to lime amendments will increase the bioavailability and phytotoxicity of arsenic, which will impair vegetative performance.
- The formation of secondary weathering products in tailings, particularly jarosite, will increase the solubility of metals compared to they would otherwise have been.

- Soil conditions resulting from the incorporation of amendments (salinity) will not be conducive to long-term vegetative success.
- As Schumm (1995) points out major floods, which will accelerate erosion, are inevitable as is the inevitability of channel movement through meandering and avulsion. Thus the erosion of STARS treated tailings is also inevitable.
- ARCO provides little substantive data or information to support a conclusion that STARS is a viable long-term remediation technology.
- Demonstration projects along Silver Bow Creek, and reclamation work conducted at other sites in Montana, Colorado and South Dakota do not support conclusions that STARS is a viable long-term remediation technology.

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Comments On

Proposed Plan: Streamside Tailings Operable Unit

by Eugene E. Farmer

August 2, 1995

GENERAL COMMENTS

Basically, this plan is a good plan. It has many things to recommend it. I believe that moving the tailings and contaminated soils to the Opportunity Ponds is a reasonable plan and removes these contaminant sources to an area that is already contaminated. However, I am concerned about using the STARS technology on some 780 thousand cubic yards of contaminated tailings/soils. I will specify my concerns in the comments that follow.

HYDROLOGY AND FLOODS IN SILVER BOW CREEK

How has this plan accounted for the fact that from time to time flood events in Silver Bow Creek will cause it to shift the location of its channel? The proposed plan suggests leaving tailings outside of the 100-year floodplain. Why have you selected such a short return period event? The impact of longer return period floods will be to erode tailings material back into the SBC channel.

While I have not seen the 1989 report by CH2MHill, Silver Bow Creek Flood Modeling Study, prepared for MDHES, the proposed plan speaks about bank full flows in Silver Bow Creek. In western interior streams, such as Silver Bow Creek, a bank full flow can be expected on an average interval of 2.3 years. Does this reflect the design return period for flood events in Silver Bow Creek? That seems woefully short.

What is the design return period for floods in the study area? I believe that a 500 year return period event has been used on many other NPL mining sites, e.g., Leadville, Colorado, Iron Mountain, California, The Blackbird Mine, Idaho (strictly speaking, not an NPL site), White King-Lucky Lass, Oregon and so on.

STARS

The use of STARS technology is an integral part of preferred alternative, #6. Although development of the STARS technology is an admirable development in the reclamation of mine waste, it appears to fall short of the criteria established by EPA for evaluating remedial options, NCP 300.430 (e)(9)(iii). Specifically, it is my view that STARS violates item (C) Long term effectiveness and permanence. It is probable that it also violates item (D) Reduction of toxicity, mobility, or volume through treatment.

STARS is a short term technology, unsuited for long term protection of riparian resources. The success that has been realized to date by the application of lime and fertilizer to tailings and soil materials containing hazardous levels of noxious metals is almost certainly bound to reverse itself over time. Lime materials applied to sulfide tailings/contaminated soils will ultimately be depleted, as will plant nutrients. As the treated materials revert to an acid soil condition the vegetal cover will be lost. How long will this serious setback take? I don't think that science can presently provide hard answers to that question. An approach that has been used on other mining sites has been to determine the total sulfur content of the system and the rates of oxidation. These calculations yield an estimate of the time required to deplete the system of oxidizable sulfur. Our longest actual experience with reclaimed tailings in tailings ponds is on the order of 20 years or so. However, we do know that the oxidation of all of the sulfide sulfur in a metaliferous pyrite system usually takes many centuries. I believe that it is also important to point out that STARS technology will not change the total metal loading in the streamside areas.

Some of the most interesting results from the reclamation of metaliferous tailings has to do with the persistence of vegetation and the result of establishing a vegetal cover on tailings. With respect to the question of vegetal persistence, the jury is still out. Over time periods of about 20 years some vegetation

ATTACHMENT A

will persist, but the vegetal cover appears to be on a long downhill slide, i.e., over time the vegetal cover is diminishing with regard to both species richness and total weight and density. For those people who understand the requirements for plant growth and persistence that result seems entirely reasonable. How long will the vegetal cover last as a result of a STARS effort? That answer is unknown, but my expert opinion is that the vegetal cover will disappear altogether within 35 to 50 years.

But, vegetal persistence is probably not the controlling factor in reducing the flow of metal ions into the environment. In those examples of tailings ponds that have been successfully revegetated, the unhappy fact is that the ponds still emit acidic drainage contaminated with metal ions. Therefore, in my opinion it is not enough that STARS cover the surface with vegetation; STARS must also demonstrate that the treatment will immobilize metal ions into the foreseeable future, certainly for more than 100 years. In the instant case that has not been demonstrated; quite the contrary. The MDHES states that both cadmium and zinc are not immobilized by STARS and arsenic may actually be mobilized by the treatment.

In a 1995 paper by Munshower, et.al.[1] the authors state that during this 6 year study the most effective treatment did not include STARS treatment at all. The data supported coversoil as the most effective treatment. They also cite cadmium, zinc, and arsenic levels as being difficult to predict as a result of the STARS treatment. As to the chief problem of implementing STARS, the authors cite the difficulty of incorporating soil amendments (lime) to a depth sufficient to maintain a healthy plant community.

The very real difficulties of incorporating lime to a depth greater than 12 to 18 inches cannot be overlooked. As we are dealing with a hazardous tailings material with an ultimate lime potential as great as 200 tons per acre furrow slice (6 inches) the question becomes one of just how much lime is really needed and how much is it possible to apply?

At this point it is important to address liming materials. STARS technology was developed using regular ground limestone (calcium carbonate) and quicklime (calcium oxide). Quicklime (calcium oxide) is completely miscible with water and forms calcium hydroxide, an extremely caustic agent. It is applied as a liquid slurry and is short lived in the tailings/soil profile. It neutralizes all acidic agents in its path and then exits the system with the first flush of water. In all likelihood, most of the hydroxyl ions remain basic and unneutralized. In simpler terms, over application of calcium hydroxide accomplishes little good. It rapidly exits the soil-water system, leaving unoxidized sulfide minerals to produce additional acid over time. In the neutralization of an acid tailings/soil system quicklime has very limited use. It can produce an immediate effect, but not a long lasting effect.

On the other hand, agricultural lime (calcium carbonate) is slower acting, but longer lasting. Agricultural lime is not miscible with water and it is nearly insoluble in pH 7 water. As the soil water pH drops, forming an acid system, the solubility of the lime in the soil water increases, neutralizing the acidity. This forms a positive feedback system that acts to neutralize soil acidity as it is formed. For this reason, standard agricultural lime is a superior liming agent to quicklime for neutralizing sulfide tailings. Furthermore, quicklime should not be counted as part of the total applied lime in a revegetation effort designed for long term success.

If quicklime is limited to short term uses, how much agricultural limestone can applied on a per acre basis? The answer depends to some degree on how finely the limestone is ground, but as a general rule it is very difficult to apply, and work into the soil more than about 20 tons per acre of finely ground agricultural lime. If one is willing to spend great time and effort you might even apply up to 30 tons per acre. If more than that is applied it is likely that the seed-bed will be made in the calcium carbonate dust. The simple truth is that there are practical limits on the amount of limestone that can be usefully applied on a per acre basis to tailings/soils. This is the principal limitation on achieving total neutralization of sulfide bearing tailings/soils and explains why it will be necessary to relime time and time again if we are trying to achieve a "permanent" long term solution.

Beyond considerations associated with the simple act of liming acidic tailings material, the long term success of reclaimed tailings and metal contaminated soils depends on the ability of the reclaimed materials to recycle plant nutrients. This is perhaps the most critical area if long term success is to be

achieved. To achieve nutrient recycling it is critically important to build the soil cation exchange capacity, by adding composted organic matter to the soil profile. In addition, it is also necessary to grow organic matter in place through the use of vegetation with high root to shoot ratios, primarily selected grasses. Organic matter additions on the order of 20 to 30 tons per acre, or even higher, would be appropriate. Such additions of organic material will also increase the water holding capacity of the reclaimed materials. That is important during the dry summer season.

Therefore, it appears to me that STARS fails on five counts as a long term remedial technology: (1) it is a short term technology; but is proposed for application to a long term problem, (2) The STARS technology relies on the application of calcium hydroxide (a noxious material) that is short lived in the tailings/soil environment and inappropriate for large scale applications, (3) liming rates will not approach the total acid potential of the tailings materials, and will therefore require regular reapplication, (4) the STARS technology has not addressed plant nutrient cycling, an absolute requirement for long term success, and (5) STARS treated areas will continue to show metal contaminated water drainage from the treated areas.

Based on the foregoing considerations, it is my considered opinion that STARS technology will not be a successful treatment for application over the long run to the Streamside Tailings Operable Unit. Therefore, my suggestion is to eschew alternative #6 and go directly to alternative #7 as the best compromise between cost and long term effectiveness based on proven technology.

---

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Robb Gillian

MONTANA STATE UNIVERSITY
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Reclamation Research Unit
Montana State University
Bozeman, MT 59717-0290
Telephone 406-994-4821

LAND REHABILITATION

RECEIVED
MAR 7 1995
NATURAL RESOURCE DAMAGE PROGRAM

22 February 1995

RECEIVED
FEB 27 1995
FISHERIES DIV.
DEPT. FISH, WILDLIFE & PARKS

Mr. Glenn R. Phillips
MT Department of Fish, Wildlife & Parks
PO Box 200701
Helena, MT 59620-0701

Dear Mr. Phillips,

With regard to your Jan. 20 letter to Neil Marsh, we at Reclamation Research agree with much of what you said. STARS was not intended to be a cure-all for streamside tailings. It is only one proposed remedial activity that may be implemented in the Silver Bow/Clark Fork system. This technology is not appropriate when tailings are in a location that will be subjected to erosion by a meandering stream in the near future. The question becomes more indistinct when we realize that the entire Rocky Mountain Range will be leveled by "natural erosion processes" at some time in the future. The question is, where should removal occur and where should another remedial activity be contemplated.

Many people are attributing a use to STARS that is much broader than was intended by the scientists who developed the process. As Dennis Neuman pointed out at the Jan. 17 meeting, STARS should be used in conjunction with other remedial activities. STARS was not proposed by its developers as a remedial activity for tailings in contact with a meandering stream. We found after one year of monitoring that this technology did not function adequately on pure tailings in direct contact with a stream. Bill Schafer did not use it in such a manner in the Governor's Demonstration project and it has not been projected for such application by the Reclamation Research Unit.

Sincerely,

Frank Munshower

Frank F. Munshower
Director, RRU

FFM:eaf
ARTS\ltrs&mem.ART-12-1 eaf

ATTACHMENT B

Montana Department of Fish, Wildlife & Parks

1420 E 6th Ave
PO Box 200701
Helena MT 59620-0701
January 20, 1995

RECEIVED
JAN 25 1995
NATURAL RESOURCE
DAMAGE PROGRAM

Mr. Neil Marsh, Program Manager
State Superfund Supervisor
Department of Health and
  Environmental Sciences
Helena, MT 59620

Dear Neil:

I wanted to send you a follow-up to the meeting on January 17 to discuss the merits of the STARS remediation technology. As you probably gathered from some of the discussion that occurred during the meeting, we are particularly concerned about leaving amended tailings in place where they will be subjected to the natural erosion processes that occur when a meandering stream moves back and forth across its valley.

When the concern of entrainment of tailings was discussed during the meeting, we heard the same argument that we have heard for some time -- that sediment bound metals are unavailable to aquatic life. We disagree with this logic. First, even with waterborne exposure, it can be legitimately argued that sediment bound metals may dissolve in the water column at some future time in response to changing water chemistry.

More importantly, metals present in the substrate are immediately available to macroinvertebrates whether they are in a dissolved form or not, because many macroinvertebrates consume sediment. Ingestion of sediment by macroinvertebrates is a passive activity, in that sediment particles are entrained on food items that are actively sought i.e. pariphyton, detritus, etc. Once contaminated sediment particles reach the low pH environment of the gut, they dissolve, are assimilated into tissues and are subsequently available to fishes or other predators that consume macroinvertebrates. For example, macroinvertebrates collected from the Clark Fork River immediately below the Warm Springs Ponds contain several hundred parts per million of copper. Early life stages of rainbow trout fed this invertebrate diet during laboratory experiments suffered mortality and reduced growth (Woodward et al. 1994; Trans. Am. Fish. Soc. 123:51-62). Clearly, food chain exposure to contaminants has important implications to Clark Fork River fishes.

ATTACHMENT C

Our position is that STARS may be a legitimate remedial technology for locations that are not likely to erode into the stream at some future date or where the lens of tailings is sufficiently thin to allow natural vegetative cover to become established; such is the case in certain segments of the Clark Fork floodplain. However, we cannot support use of STARS in areas where entrainment of tailings is likely to occur in the near or distant future.

In conclusion, we feel that removal of all tailings from erosion prone areas is the only effective way to remediate impacts to the fishery.

Sincerely,

Glenn R. Phillips
Acting Chief
Habitat Protection Bureau

cc: Wayne Hadley, FWP
Dennis Workman, FWP
Bob Fox, EPA
Frank Munshower, MSU
Robb Collins, NRDA

REBUTTAL OF ARCO'S REPORTS ON STARS

Final Report

Prepared for:

State of Montana
Natural Resource Damage Litigation Program

Prepared by:

Hagler Bailly Consulting, Inc.
P.O. Drawer O
Boulder, CO 80306-1906
(303) 449-5515

Contact

Ann S. Maest, PhD

October 18, 1995

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Testifying Expert:

Ann S. Maest, PhD

Ann S. Maest

October 18, 1995

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TABLES

FIGURES

ACRONYMS

ARCO	Atlantic Richfield Company
CFR	Clark Fork River
TOC	total organic carbon
NCV	net carbonate values
NRV	naturally revegetated soils containing tailings
NRT	non-revegetated tailings
RTC	Racetrack Creek
XRF	x-ray fluorescence
EMPA	electron microprobe analysis
MCL	maximum contaminant level
SMCL	secondary maximum contaminant level
SI	saturation index

INTRODUCTION

My review of ARCO's submittals on restoration of the Clark Fork River (CFR) sites will focus primarily on the Expert Report of Andy Davis, PhD (July 13, 1995). Dr. Davis addresses the long-term stability of amending the streamside tailings in Section 2.0 ("The Geochemistry of Riparian Tailings"). In this section he also considers the potential for vertical metal transport to groundwater. Both of these issues were raised by the State of Montana as crucial study elements for the successful restoration of the CFR sites. An evaluation of Dr. Davis' work on long-term stability of amended tailings and metal transport to groundwater will be discussed below.

LONG-TERM STABILITY OF TAILINGS AMENDMENTS

Dr. Davis assessed the long-term stability issue (and metal attenuation) by conducting the following analyses on amended and unamended riparian tailings and soils: 1) bulk metal concentrations 2) mineralogical analysis; 3) humidity cell tests; 4) pore water chemistry; and 5) geochemical modeling of metal attenuation. An evaluation of these analyses is presented below.

The samples used for the long-term stability studies were collected from the Governor's Project area (amended tailings) and from three other locations downstream of Warm Springs Ponds (unamended tailings). For the Governor's Project locations, the upper samples are amended (GP1 0-12", GP1 12-15", GP2 0-12", GP2 12-20", GP3 0-12", GP3 12-15"), GP1 18-22" and GP2 20-28" are unamended, and GP1 >22" and GP3 15-20" are buried A horizon samples.

Bulk Metal Concentrations

Total concentrations of arsenic, cadmium, copper, lead, zinc, soil paste pH, percent total organic carbon (%TOC) and Net Carbonate Values (NCV) were determined on three amended soils at the Governor's Project (GP1, GP2, GP3) and on three unamended soils: naturally revegetated soils containing tailings (NRV), non-revegetated tailings (NRT), and tailings mixed with overbank deposits near Racetrack Creek (RTC). Results are presented in Table 2.2 in the Davis Expert Report.

The analytical results for bulk metal concentration showed poor reproducibility and poor agreement with standard reference samples. The metal/metalloid analyses were conducted by x-ray fluorescence (XRF), which is a semi-quantitative method. The duplicate analysis for NRT shows poor reproducibility (>±25%) for copper (±59%), zinc (±33%), and NCV (±72%). In addition, the analyses conducted on Standard Reference Materials showed poor agreement with recommended standard concentrations of zinc, arsenic, and lead.

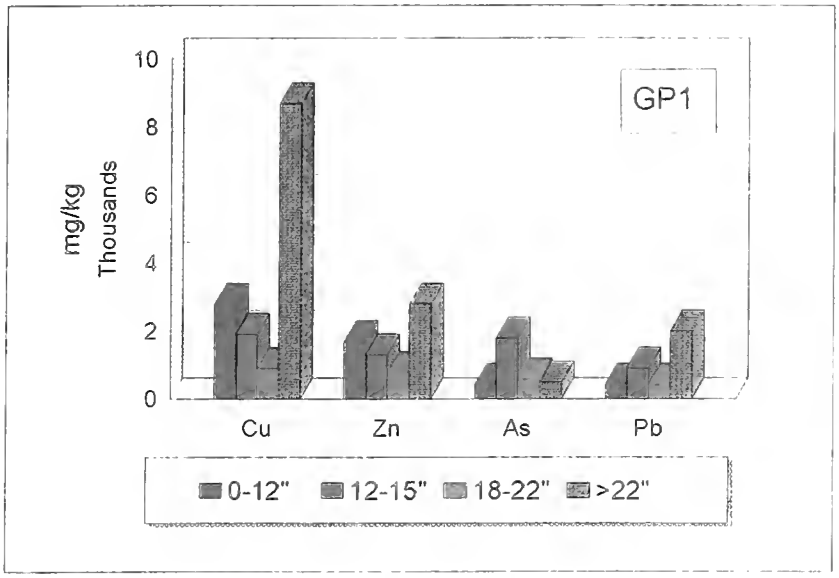
Davis concluded that the bulk metal results were characteristic of a soil/tailings mixture and did not show any trends related to amendments or weathering (Davis report, pg. 2.6). Putting aside the inherent analytical problems for the moment, and assuming that concentrations are only semi-quantitative, some trends are apparent when examining bulk concentrations in the amended tailings and the unamended material below these locations, contrary to Davis' conclusions. Bulk concentrations of copper, zinc, arsenic, and lead for GP1 and GP3 are shown in Figure 1. In the buried A horizons of GP1 (22") and GP3 (15-20"), copper and zinc concentrations are higher than in the overlying tailings. The same is true for lead in GP1. Assuming that the historic A horizon metal concentrations were at background levels, this indicates that copper, zinc, and lead (in GP1) have migrated from the tailings downward to the old soil horizon and precipitated at the tailings-soil horizon interface. The lower soil paste pH of GP1 indicates that downward migration of acidity has also occurred. The mobility of contaminants precipitated at that interface is a function of the solubility of the phases with which they are associated and the geochemical conditions present over time at those depths in the soil profile.

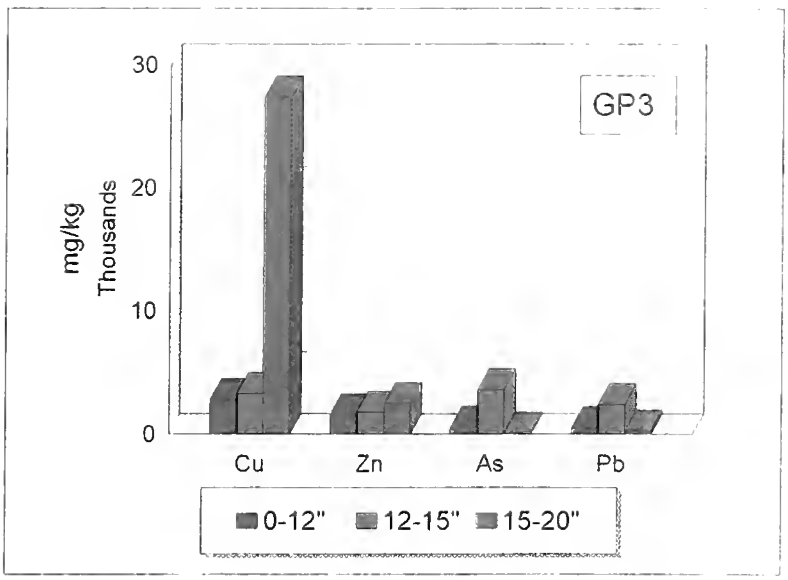
"Mineralogical" Analysis

Samples were analyzed by Electron Microprobe Analysis (EMPA), which will give the chemical composition of the grains being examined but will not give the structural information necessary to determine mineralogy, as would x-ray diffraction. A number of the phases, especially the iron oxyhydroxides, are likely not crystalline, so EMPA is a good method to use to obtain some chemical information about these phases. However, there are a number of very soluble hydrated iron-containing oxidation products that may have very similar chemical formulas as the less soluble jarosite but that would not be able to be distinguished from jarosite by EMPA. For example, melanterite ($FeSO_4 \cdot 7H_20$), rozenite ($FeSO_4.4H_2O$), szomolnokite ($FeSO_4 \cdot H_2O$), and copiapite ($Fe^{2+}Fe_4^{3+}(SO_4)_6 \cdot 2H_2O$) are all very soluble hydrated iron sulfate minerals (Nordstrom, 1982) that would look to EMPA like jarosite ($KFe_3(SO_4)_2(OH)_6$), except for the presence of potassium. No information on the actual composition of the phases as determined by EMPA was provided, so it is not clear whether potassium was actually present and in what stoichiometric amounts. In addition, jarosite and ferric hydroxide are not stable for more than a season (Nordstrom, 1982). Jarosite will decompose to ferrihydrite or geothite (Nordstrom, 1982) and can release associated heavy metals in the process. Therefore, Davis' claim that secondary minerals serve as metal sinks for arsenic, copper, lead, and zinc (Davis report, pg. 2.9) is not justified.

Unfortunately, mineralogical analyses were not conducted at the same intervals for which bulk chemistry was determined, so the solubility-controlling phases for these contaminants (copper, zinc, and lead) are not known. For example, mineralogical analyses were conducted on a *composited* GP1 sample that included material from all depths (0-22"). Figure 2.9 in the Davis report shows some of the mineralogy in this composited sample, including iron/manganese oxyhydroxides containing arsenic, copper, lead, and zinc, and jarosite containing lead, arsenic, and copper. A jarosite particle containing 19% lead and 6% arsenic is also shown for the NRT sample (0-6") (Figure 2.7 in Davis report). Depending on the

Figure 1
Bulk Concentrations of Metals and Arsenic in GP1 and GP3





Source: Davis discovery materials.

geochemical conditions in the soil/tailings profile, the oxyhydroxides may provide at least a temporary sink for contaminants. However, as discussed above, the "jarosite" identified by EMPA may actually be more soluble hydrated sulfate minerals and/or the jarosite may weather to iron oxyhydroxides under more dilute water or higher pH conditions (Nordstrom, 1982). Under these conditions, jarosite can release the lead, arsenic, and copper associated with it to the interstitial water when that portion of the soil profile becomes saturated (or it may be present in soil water in the unsaturated zone). Dr. Davis contends that precipitation of secondary minerals removes metals from solution (Davis Expert Report, pg. 2.12). However, at least some of the "secondary minerals" in the tailings and soils will actually *increase* the mobility of contaminants in the streamside tailings over what the mobility would have been before the secondary minerals were formed.

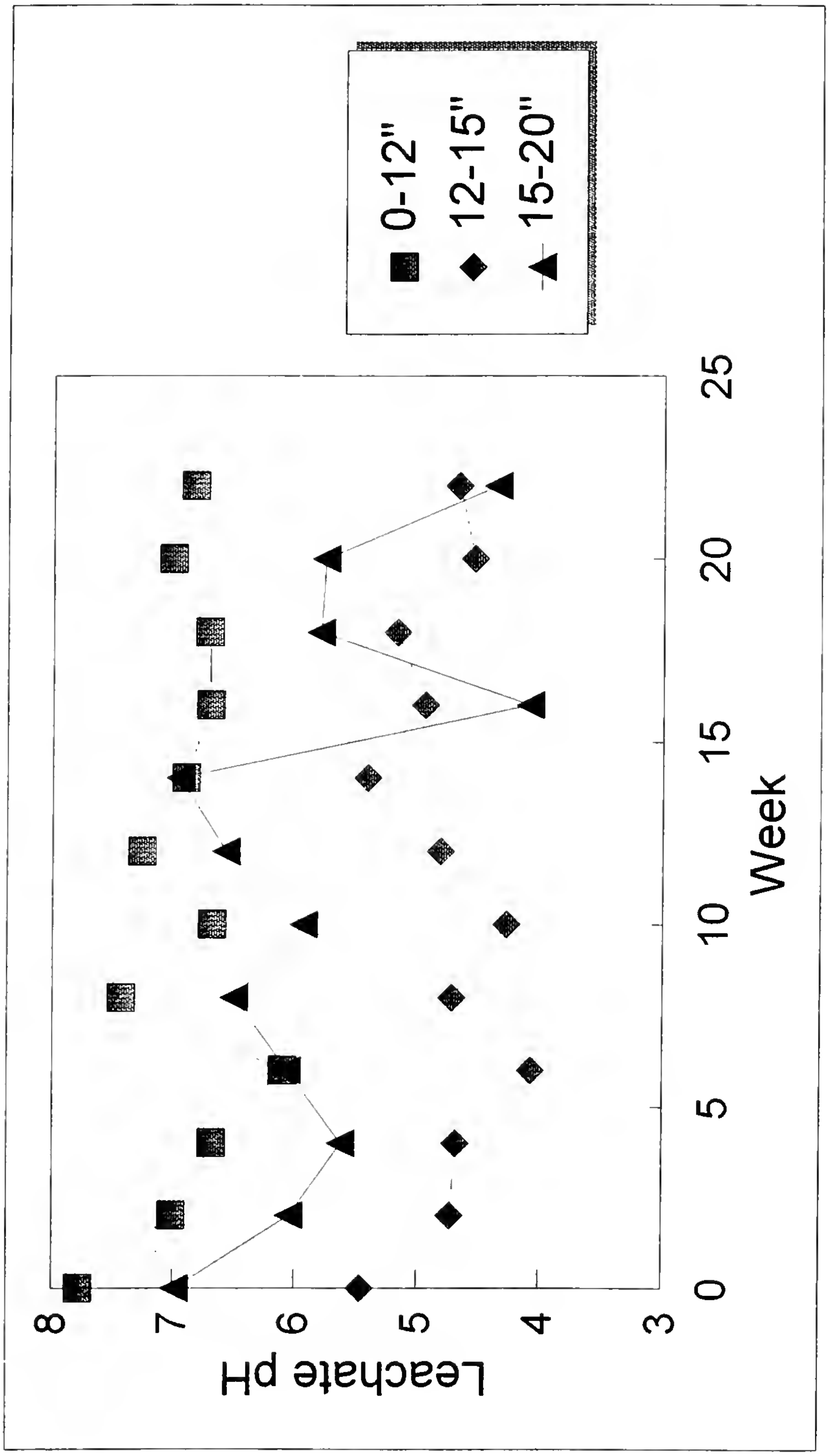
Although the presence of phosphate minerals indicates that some portion of the lead, for example, has a reduced "availability," no systematic analyses were conducted to determine how important these mineral phases are in terms of the percentage of total metal that is held in these phases.

Humidity Cell Tests

Davis concludes that "humidity cell experiments clearly show that lime amendments and revegetation have had a significant impact on soil acidity. Lime amendments have increased neutralization capacity, and increased soil pH, resulting in long-term geochemical stability." (Davis 1995, pg. 2.7) The humidity cells tests were conducted over a 22-week time frame on the amended and unamended samples described above. Leachate pH, copper, ferrous iron, total iron, specific conductivity, and NCV were determined. However, only leachate pH and NCV were reported and only in figures (Davis 1995, Figures 2.3, 2.4, 2.5, and 2.6). Spread sheets with leachate pH, copper, ferrous iron, total iron, and specific conductivity were found in discovery materials.

Davis states that leachate pH from the upper amended zones in the Governor's Project samples is higher than that in the deeper unamended soils (pg. 2.6; Figures 2.3, 2.4, 2.5). However, according to Table 2.2 in the Davis Report and information found in discovery materials, this is not true for the GP3 samples. Leachate pH data for GP3 humidity cell samples (from discovery materials) is plotted in Figure 2. The leachate pH of the deeper sample (15-20", buried A horizon) is actually *higher* than the pH of the sample collected above it (12-15", amended). Assuming that the data found in discovery is correct, this indicates that there is variability in amended and unamended pH values, depending on the location. The pH of the original soil at this location is apparently higher than that of the amended tailings above it, even though metal concentrations are higher at this depth (see discussion under "Bulk Metal Concentrations" above). Because there is so much heterogeneity in the streamside tailings, it is important to conduct many analyses to determine what is "representative" of the tailings and associated materials.

Figure 2
Leachate pH values from Humidity Cell Tests of GP3



Source: Davis discovery materials.

The presence of "verdant grass cover" at the RTC site may be a function of the fact that streamside tailings at this location are mixed with or covered by relatively clean overbank deposits. The pH of humidity cell test leachate from the RTC sample is compared to that of the upper amended soil samples at the Governor's Project in Figure 3. The pH of RTC leachate is at least as high as that from the amended tailings, suggesting that the mixing of tailings with less contaminated materials such as overbank deposits may go as far or further toward ameliorating the release of contaminants from the tailings as mixing with amendments. And the cleaner natural materials (e.g., overbank deposits) will probably have longer lasting neutralization potential than the lime/limestone mix used in the amendments because carbonates and silicates providing neutralization are less soluble than lime.

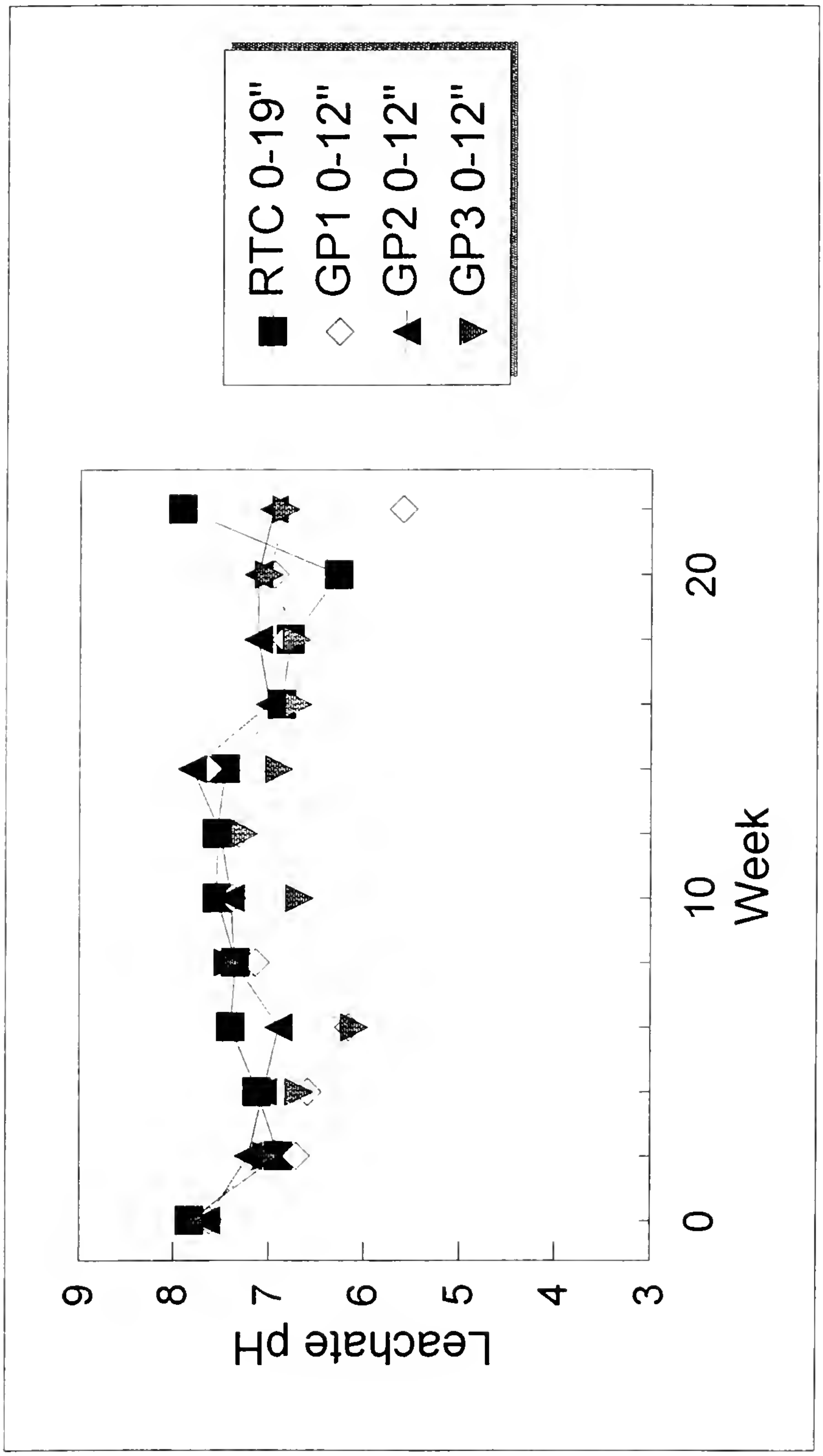
Leachate copper concentrations are shown in Table 1. Many of the copper values are reported as "INT" (sample matrix interference) or "NA" (not analyzed for ferrous iron if pH >4.50). However, for example, nearly all of the leachate pH values for Week 0 were higher that 4.50, and copper values are shown for all samples for that week. The key for "NA" must be in error. Samples were analyzed using the Hach DR 2000.

The highest leachate copper concentrations are for the non-revegetated tailings (NRT) sample, although the reproducibility of the analyses is obviously not very good (see Table 1). For example, the Week 0 results for sample NRT 0-6" are 113, 4.01, 3.56, and 118 mg/l (Table 1). Leachate copper concentrations for GP3 are plotted in Figure 4. Although there are many missing analyses, it is clear that a substantial amount of copper is leaching from the amended 12-15" depth and from the buried A horizon sample (15-20"). Bulk metal concentrations were highest in the buried A horizon at this location (see Figure 1), and the results from the humidity cell tests show that at least some of this copper can be mobilized from the soils. The lowest leachate copper concentrations (looking only at Week 0, when there was an analysis on every sample) are in the RTC and the upper amended samples from the Governor's Project samples. This is another indication that mixing with cleaner, native soils rather than with amendments, may be very effective in reducing the leachability of contaminants from streamside tailings.

Soil Pore Water Chemistry

Soil pore water concentrations are presented in Table 2.3 in the Davis Report. The shallow samples were collected from 4 to 6" below the surface of the amended tailings, while the deep samples were collected approximately 2" below the amended-unamended tailings boundary. There are many missing analyses for the shallow GP2 samples. The RTC sample had the lowest concentrations and no MCL or SMCL exceedences. All other samples had extremely elevated concentrations of certain contaminants, especially sulfate, cadmium, zinc, and copper, and many MCL/SMCL exceedences. Davis concludes that the deeper, unamended soils are more acidic (than the amended soils), and have higher metal concentrations (Davis report, pg. 2.9). However, concentrations of zinc, an important aquatic life toxicant, were particularly high (>1 mg/l) in both the shallow and deep portions of the GP samples. In either 1994 or 1995, concentrations of cadmium, copper, and zinc were higher in the deeper unamended

Figure 3
Comparison of Humidity Cell Test Leachate pH Values in Unamended (RTC) and Amended (GP) Soils



Source: Davis discovery materials.

Table 1
Leachate Copper Concentrations from Humidity Cell Tests (mg/l)

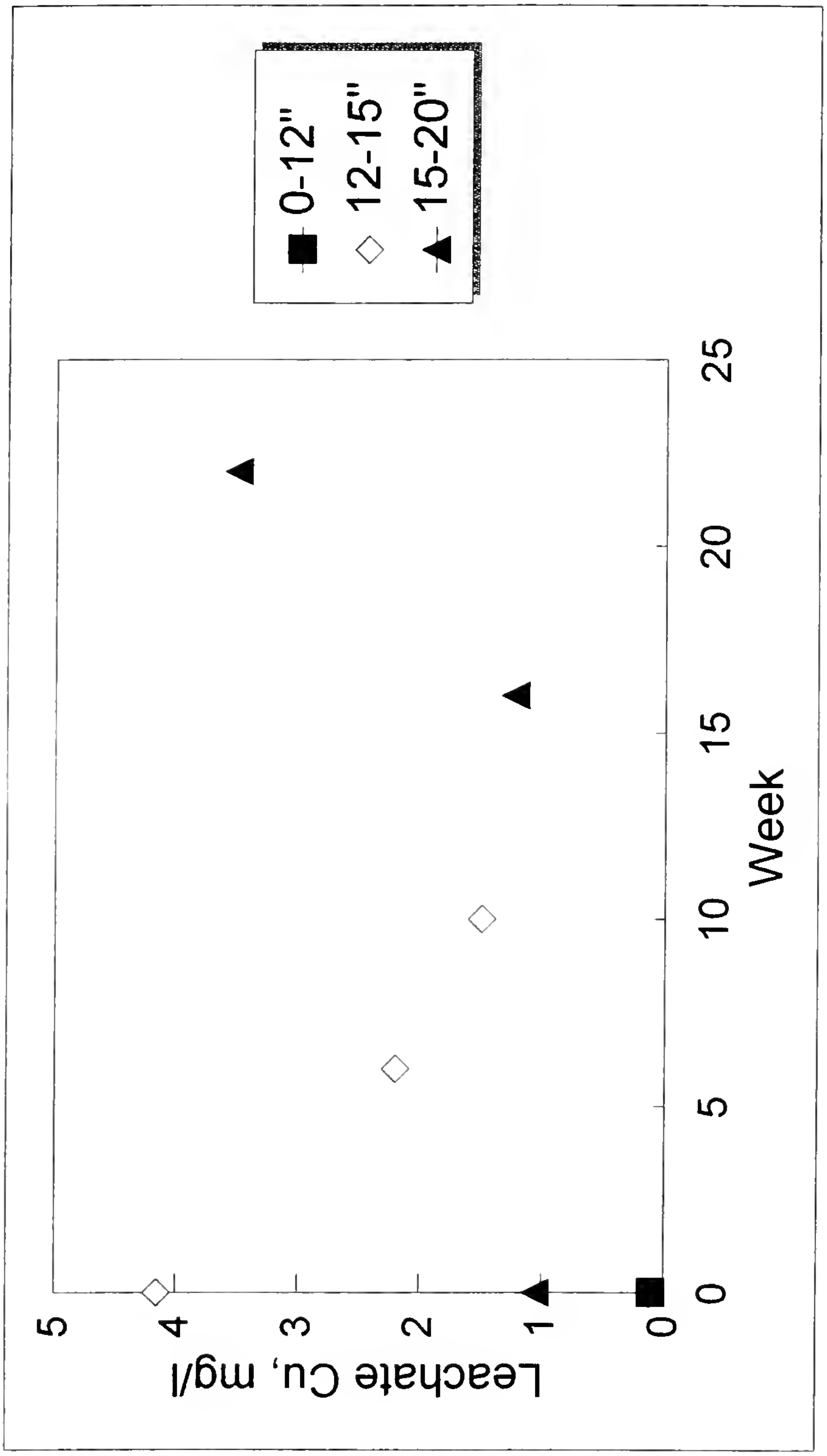
SITE NAME	8/18/94 WK0	9/1/94 WK2	9/15/94 WK4	9/29/94 WK6	10/13/94 WK8	10/27/94 WK10	11/12/94 WK12	11/23/94 WK14	12/8/94 WK16	12/2094 WK18	1/5/95 WK20	1/20/95 wk22
RTC 0-19"	0.17	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NRT 0-6"	113.00*	INT.	NA	NA	26.00*	16.00*	191.00*	NA	29.50*	NA	153.5*	114.5*
NRT 0-6"	4.01	INT.	NA	18.50*	18.50*	50.50*	NA	NA	12.50*	NA	42.5*	44.0*
NRT 6-15"	4.33	INT.	18.00*	33.00*	33.00*	18.50*	19.00*	22.00*	16.50*	11.5*	24.5*	88.0*
NRV 0-6"	0.34	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NRV 6-8"	6.40**	INT.	3.89	2.79	3.00*	NA	NA	3.88	2.13	NA	3.73	3.48
GP1 0-12"	0.71	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
GP1 12-15"	0.58	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
GP1 18-22"	7.90**	INT.	2.29	3.66	5.50*	2.86	100.50*	2.77	3.50*	2.5*	3.0*	9.0*
GP2 0-12"	0.18	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
GP2 12-20"	0.08	NA	NA	NA	NA	NA	NA	NA	NA	0.5*	NA	NA
GP2 20-28"	0.18	NA	NA	0.51	NA	NA	NA	NA	NA	NA	NA	NA
GP3 0-12"	0.1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
GP3 12-15"	4.15	INT.	NA	2.2	NA	1.5	NA	NA	NA	NA	NA	NA
GP3 15-20"	1.05	NA	NA	NA	NA	NA	NA	NA	1.23	NA	NA	3.5*
NRT 0-6"	3.56	INT.	66.50*	41.50*	47.50*	0.47*	24.50*	35.00*	23.00*	15*	53.5*	47.0*
NRT 0-6	117.50*	INT.	NA	NA	59.50*	1.54*	NA	NA	NA	30*	NA	NA

Samples were analyzed using the DR 2000 instrument (HACH).

INT.= Interference with sample matrix was encoountered when running the sample on the DR 2000.
NA.= If pH of the sample is above 4.50, then analysis for Ferrous Iron was not determined.

* = Samples were diluted 1:50 in D.I. water.
** = Samples were diluted 1:10 in D.I. water.

Figure 4
Humidity Cell Test Leachate Copper Concentrations in GP3



Source: Davis discovery materials.

sections of both GP1 and GP2 that are closer to underlying groundwater. So, even if, as Davis concludes, concentrations are lower in the shallower amended portions of the soils, his results show that the entire depth of streamside tailings must be amended (or mixed with cleaner soils) for groundwater to be protected.

Dr. Davis states that "in deeper layers, reduction in oxygen availability will limit future sulfide reactivity" (pg. 2.10). However, the high concentrations of metals in the deeper zones suggest that more soluble minerals, possibly metal sulfates produced from weathering of sulfides in overlying tailings, are controlling metal concentrations. While the higher concentration of metals in the deeper unamended samples indicates that amendments may decrease dissolved concentrations, it also demonstrates, as discussed above, that if the *entire* tailings depth is not amended, the benefits of amendments are negligible in terms of potential movement of contaminants closer to the water table.

Geochemical Modeling of Potential Metal Attenuation

Four of the soil pore water compositions (NRT, GP2 deep, GP2 shallow, RTC) were analyzed using the geochemical model MINTEQ to determine if the solid phases identified by EMPA were predictable (Davis report, pg. 2.10). However, the lack of correspondence between samples used for "mineralogical" analysis and those used for modeling make it difficult to confirm whether the minerals predicted to precipitate by MINTEQ actually exist in the soil column. Saturation indices for some of the secondary minerals are plotted in Figure 2.11 in the Davis Report. Of the samples shown in Figure 2.11, "mineralogical" analyses were only conducted on the NRT sample. A number of photomicrographs of GP1 are shown in the Davis Report, yet the pore water chemistry for this sample was not chosen for modeling. This is especially confounding because of all the missing values in the GP2 shallow analysis (see Table 2.3 in Davis Report), which was used for modeling.

MINTEQ output files for GP1 deep, NRT, GP2 deep, and RTC deep were found in discovery materials. Sulfide phases were not shown in the output tables, so Davis' conclusion about sulfides being less soluble with depth cannot be confirmed by the modeling results presented. The MINTEQ output file for GP1 deep, which was not presented in the Davis report, showed undersaturation for numerous heavy-metal sulfates, phosphates, carbonates, and hydroxides, including those containing lead, copper, cadmium, iron, arsenic, and zinc (Bates Stamp DAV000000005-DAV000000008). Most of these phases are also shown to be undersaturated (likely to dissolve) in MINTEQ output for the NRT, GP2 deep, and RTC deep samples.

Phases identified by EMPA in the NRT sample include primary zinc and iron sulfide minerals (with limited weathering halos, suggesting these minerals may be undersaturated), pyrite with rims of iron oxyhydroxide, jarosite, and an aluminum-sulfur phosphate phase with 14% lead. The MINTEQ analysis for the NRT sample predicts that (amorphous) iron oxyhydroxide would tend to dissolve (SI $\approx$ -1), yet this phase was observed in the NRT sample. Amorphous iron oxyhydroxides have a higher solubility than crystalline iron oxyhydroxides, so this is not necessarily an unexpected result. Jarosite would tend to precipitate (SI $\approx$ 1.3), and it was

observed in the NRT sample. Plumbogummite (a lead-aluminum phosphate mineral) would also tend to precipitate (slightly oversaturated), and it was observed in the tailings sample.

No EMPA results were shown for the GP2 samples, but the phases identified in GP1 are compared here to results from MINTEQ analysis of GP2 pore waters. GP1 and GP2 both have a 0-12" amended root zone/grass underlain by 3-8" of amended tailings and 4-8" of unamended material. The pH values of soil pore waters for GP1 shallow was 6.79/7.15; the pH of GP2 shallow was slightly lower at 6.43. The pH of GP1 deep was 6.38/6.89; the pH of GP2 deep was lower at 5.56/5.02. Phases tentatively identified by EMPA in GP1 included pyrite with thick alternation rims of oxyhydroxide, sphalerite with coatings of jarosite, iron oxyhydroxide particles with arsenic, copper, and lead, and an aluminum-sulfur phosphate phase with 25% lead. MINTEQ analysis of GP2 pore waters predicted that jarosite would tend to dissolve in GP2 shallow and precipitate in GP2 deep because of the lower pH in GP2 deep, and jarosite was identified in GP1. Iron oxyhydroxide and plumbogummite were predicted to be near saturation in both shallow and deep GP2 samples, and both were identified in GP1.

There seems to be reasonable agreement in a very qualitative sense, then, between phases identified by EMPA and results from MINTEQ modeling of pore waters from the tailings that were *shown* in the Davis report. However, as discussed above, EMPA does not provide structural information necessary to determine the exact mineralogy. In addition, as also discussed above, important results from the MINTEQ output files were excluded from the Davis report.

The presence of high concentrations of metals and other contaminants in the pore waters, especially in deeper portions of GP1 and GP2 (see Table 2.3 in Davis report) indicates that the more soluble phases identified, such as metal-rich hydrated sulfates, are controlling metal concentrations in the streamside tailings pore waters. This seems to be confirmed by the MINTEQ results found in discovery materials, where many of these hydrated metal sulfates were predicted to be undersaturated. At higher pH values jarosite is more soluble, so amendment of tailings that have weathered and formed jarosite from primary sulfides would tend to generate high concentrations of metals, especially of those metals associated with the precipitated jarosites. According to the EMPA analyses presented in the Davis report, the metals associated with jarosites include lead, arsenic, and copper (see Figures 2.7b and 2.9b in Davis Report). The association of arsenic with jarosites may partially explain why higher pH values in amended tailings are associated with higher arsenic concentrations. As the metal/metalloid-rich jarosites are dissolved at the higher pH values generated from added amendments, arsenic, lead, and copper will be released from the jarosites.

At higher pH values, lead and copper may become partially adsorbed to materials in the soil/tailings column, but arsenic would likely remain dissolved in pore waters because adsorption of arsenic decreases with increasing pH. A pronounced drop in arsenic K_d values in riparian soils at higher pH values is shown in Figure 2.12 in the Davis report. Although Davis points out that the K_d value for arsenic is still quite high at pH values of the GP samples (pg. 2.12, Davis report), dissolved arsenic concentrations are substantially higher in the

amended, higher pH GP2 pore waters than in the deeper GP2 sample (see Table 2.3, Davis report). Depending on hydrologic and geochemical conditions in, adjacent to, and underlying the streamside tailings, this dissolved arsenic can be transported to underlying groundwater and adjacent streams.

POTENTIAL FOR METAL TRANSPORT TO GROUNDWATER

Dr. Davis conducted two types of experiments to evaluate the potential for vertical transport of contaminants to groundwater. He concludes that "vertical transport of metals to groundwater is minimal under conditions most likely to be present in the floodplain environment (pg. 2.15)" and that "because the metals are not effectively transported to groundwater, it is also unlikely that they could be laterally transported to the CFR via the groundwater pathway (pg. 2.16)."

The first type was soil leaching experiments, which were used to determine the rate of metal leaching. Three intact Clark Fork River (CFR) floodplain samples were collected in columns and leached with 500 ml of distilled water each day. The soils contained varying amounts of tailings (see Figures 2.14, 2.15, 2.16 in Davis Report). The discharged water from the bottom of the column was analyzed for arsenic, cadmium, copper, lead, and zinc. Tables with the actual measured concentrations of these contaminants in the leachate were not provided.

The second type of experiment was metal partitioning experiments. In these experiments, 75g of dried soil from unknown locations and of unknown composition was packed into 60-ml syringes. The soils were saturated with deionized water and equilibrated for approximately one day. The water was then removed and analyzed for the same elements listed above. The results from these experiments were used to determine the partitioning of metals/metalloids between soils and soil solution (K_d values). However, the limited information provided on experimental design indicates that these are leaching experiments rather than adsorption or metal partitioning experiments. Therefore, conclusions about attenuation cannot be drawn from these experimental results.

Finally, groundwater from wells below tailings within 50 feet of Silver Bow Creek was collected and analyzed for pH, arsenic, cadmium, copper, iron, lead, mercury, and zinc. The results are listed in Table 2.8 of the Davis Expert Report.

The results of these studies will be discussed separately below.

Soil Leaching Experiments

The leaching rate of metals and arsenic determined from the soil leaching experiments are shown in Figure 2.17 of the Davis report. Generally, the rate of leaching decreases with time; however, there are increases in leach rate at 25 days for zinc, at 17 days for arsenic, and at 19 days for cadmium. The experimental conditions poorly mimic those that streamside tailings are exposed to (alternating wet and dry cycles) and that would result in the formation of

secondary weathering products. Because 500 ml of deionized water was added to the columns each day, weathering products did not have a chance to accumulate in the columns the way they would in actual streamside tailings. The high application rate of water essentially assures that the leach rate will decrease with time. However, unlike Davis' conclusion that secondary weathering products have slow kinetics of dissolution (pg. 2.14), the results strongly indicate that there is an initial flush of contaminants from streamside tailings when water moves through dry deposits (analogous to the first snow melt or to thunderstorm events). The concentrations of metals and arsenic are quite high. For example, on day 5, zinc concentrations were 700 mg/l, copper concentrations were over 40 mg/l, and arsenic concentrations were approximately 16 mg/l, assuming that 500 ml were collected from the bottom of the column. If less liquid was collected, the concentrations measured in the leachate would have to be even higher to achieve the leach rates shown in Figure 2.17 of the Davis report. The high concentrations leached from the floodplain soils indicate that these materials are still contaminant generators after up to 100 years of weathering.

According to the microprobe analysis results shown in Table 2.6 in the Davis report, there are abundant sulfides remaining in the floodplain soils. Of the samples listed in Table 2.6, only one is a tailings sample (SC0003), and a complete analysis of the sample is not provided. The sulfides in the floodplain soils will weather to more soluble metal-rich sulfates, which can become solubilized upon contact with water. Therefore, according to the results presented in the Davis report, we can expect a high-concentration flush of metals and arsenic from the floodplain soils when the soils are exposed to water after a dry period.

Metal Partitioning Experiments

As discussed above, the "metal partitioning" experiments are more leach experiments than they are adsorption or metal partitioning experiments. In metal partitioning experiments, the metal must be present in the solution you are adding to the soils, so the distribution of metals between the initial solution and the soils can be determined by measuring the difference between concentrations in the initial and final solutions. The metal partitioning experiments described in Section 2.5.2 of the Davis report are very similar to those discussed above, in that deionized water was applied to soil. The only differences are that a much smaller amount of soil was used and the soil was saturated in the "metal partitioning" experiments. Again, no tables of data in the leachate were provided, only K_d values (Table 2.7, Davis report) presumably derived from the leachate concentrations. The experimental design of the "metal partitioning" experiments is so questionable that the results cannot be considered meaningful. Therefore, Davis' conclusion that "attenuation of metals ... suggests that vertical transport of metals to groundwater is minimal... (pg. 2.15)" is not supportable by the metal partitioning experiments he conducted.

Concentrations in Groundwater Below Tailings

The concentrations of contaminants in groundwater below tailings along Silver Bow Creek are presented in Table 2.8 in the Davis report. The depth below tailings or the screened interval of the sample are not shown. The pH values of the samples are indeed near neutral, and the concentrations of arsenic, cadmium, copper, and lead are generally low, as indicated in the Davis report (pg. 2.16). However, the concentrations of zinc in three of the samples are quite high -- 640, 4,250, and 6,400 μg/l. The aquatic life criteria for zinc at a hardness of 100 mg/l are 120 and 110 μg/l for the acute and chronic criteria, respectively. Groundwater flow directions along Silver Bow Creek are generally toward the creek (Maest and Metesh, 1995); therefore, contaminants in groundwater proximal to Silver Bow Creek (or the Clark Fork River) can be transported directly to the creek. Because contaminant concentrations in Silver Bow Creek are lower than those in groundwater, the groundwater concentrations will be diluted upon mixing with the creek. However, the concentrations in three of the wells would need to be diluted by factors ranging from 5.8 to 58 times to achieve water quality goals.

Concentrations in groundwater below tailings in Lower Area 1 (Colorado Tailings area) were also reported in Maest and Metesh, 1995, and are displayed in Table 2. The pH of groundwater from these wells is fairly low, and the concentrations of contaminants are substantially higher than those reported in Table 2.8 of the Davis report. Groundwater flow directions in the Colorado tailings area are toward Silver Bow Creek (Maest and Metesh, 1995), and groundwater from this area does add contaminants to Silver Bow Creek (Montana Aquatics Report, 1995). The data presented in the Davis report and in reports by the State of Montana clearly show that groundwater has been contaminated by metals and arsenic as a result of leaching of tailings material. Groundwater flow directions in floodplain materials are toward the creek, and the high concentrations of metals added to the creek from groundwater is on ongoing threat to existing and potential future aquatic life that may be present in Silver Bow Creek and the Clark Fork River.

REFERENCES

Davis, A. 1995. Expert Report of Andy Davis, PhD. July 13.

Maest, A.S., J. Metesh, R. Brand. 1995. Butte Groundwater Injury Assessment Report. State of Montana Natural Resource Damage Litigation Program. January.

Nordstrom, D.K. 1982. Aqueous pyrite oxidation and the consequent formation of secondary iron minerals. *Acid Sulfate Weathering*. Soil Science Society of America, Wisconsin, 37-56.

Table 2
Groundwater Quality Data from Well BMW-4 (μg/l or pH units).

Well #	Screened Interval (ft)	Sampling Date	pH	Arsenic	Cadmium	Copper	Lead	Zinc
BMW-4A	5.5-11.5	11/09/89 04/24/90	4.0 3.9	2,300 2,100	260 316	25,000 28,100	260 204	86,000 109,000
BMW-4B	27.5-37.5	11/19/89 04/24/90	5.0 4.5	630 2,040	410 410	11,000 12,500	63.0 86.7	120,000 117,000

Rebuttal of ARCO's Reports on STARS

submitted to

Montana Department of Justice
Natural Resource Damage Program
Old Livestock Bldg., 1810 E. Lockey
P.O. Box 201425
Helena, MT 59620

October 1995

by

Lawrence A. Kapustka, Ph.D.
ecological planning and toxicology, inc.
5010 S.W. Hout Street
Corvallis, Oregon USA 97333-9540
phone: 503/752-3707 FAX: 503/753-9010

Lawrence A. Kapustka

Lawrence A. Kapustka, Ph.D.

Table of Contents

Materials Reviewed

Copies of reports prepared for ARCO were provided by the State of Montana [17 July 1995] for review. The reports were:

1. Redente: Report on Terrestrial Injuries and Restoration (including STARS)

2. Davis: Report on Sediments and STARS.

Supplemental materials from discovery disclosures by Redente related to the preparation of reports were also supplied for this review.

Earlier reports and background materials related to this case (identified to ARCO prior to and during my deposition) were also examined. In addition, a number of journal articles and books were reviewed to form the supporting base for conclusions and comments presented herein.

Summary

A review of literature on liming effects and detailed study of Redente's Report reinforces the State's concerns regarding permanence of STARS. Arsenic toxicity is not relieved by liming. Immobilization of toxic metals is restricted to the zones receiving lime and will not have any ameliorating influence in the deeper tailings deposits. Therefore, the treatment will not retard movement of metals into ground water or surface water. The high quantities of lime required to afford long-term neutralization of acid-generating tailings adversely affects plant growth and nutrient cycling processes. Enhanced nitrification leading to leaching loss has been reported in other situations. Finally, no information is provided in the report by Redente to conclude that STARS has lead to an increase in soil organic matter or improved the microbial community processes.

Specific opinions developed from the literature and Redente's report are:

- Although arsenic solubility is partially lowered by calcium, the light textured slickens soils with high As concentrations will continue to pose phytotoxic risk to plants.
- Liming temporarily immobilizes many hazardous metals, however, as neutralizing capacity declines, the metals again become bioavailable.
- High rates of liming are known to reduce plant growth.
- Root growth in lime-treated acid soils is restricted to neutralized "pockets" and excluded from poorly mixed zones. This results in added interference among plants reducing productivity and increasing surface erosion.
- High density root growth and associated acid generation by the roots in the neutralized "pockets" can result in increased mobilization of metals in adjacent poorly mixed and unmixed soil zones.
- Nutrient cycling processes are disrupted by liming.
- Additions of large quantities of lime, especially in sandy soils, results in ionic and osmotic stress to plants during dry periods.
- Subjectively sampled soils and one-time, static measures cannot be used to draw comparisons of dynamic soil processes.
- No evidence is provided to support claims of long-term efficacy of STARS.

1. Background

The Streamside Tailings and Reclamation Studies (STARS) have included laboratory and field trials to devise a method to neutralize acidic tailings (slickens) and immobilize associated hazardous substances such as As, Cd, Cu, Pb, and Zn along the Silver Bow and Clark Fork River. STARS is intended as a one-shot, no maintenance remediation/rehabilitation effort. Several technical assumptions must be met for this to be possible:

1. The quantity of lime added must be sufficient to off-set acid generation indefinitely.

2. The neutralizing capacity of lime must remain chemically accessible (i.e., not become armored).

3. Mixing in the soil must be thorough so as to create essentially a homogeneous soil with respect to acidic and limed pockets. To be effective, the scale of interest is the volume occupied by roots and their associated microflora -- (i.e., between <mm^3 and cm^3)

The design criteria described by the developers of STARS show recognition of limitations of STARS. Groundwater must be below the treatment zone. Effectiveness of treatment is restricted to the mixing zone (48" for deep plow incorporation methods) and is most effective at depths of 6" or less. Phytotoxicity studies conducted by the State on slickens demonstrated that mixing toxic slickens with clean reference soil alleviated toxicity.

Several issues remain, largely because the study design used to demonstrate STARS efficacy. Inadequate pre-treatment characterization of field plots coupled with substantial heterogeneity challenges interpretations of efficacy. Several key biological/ecological issues regarding the permanence of the method remain. The following discussions are drawn from a vast literature on the subject of liming and revegetation. In my opinion, the strong message that emerges in the published works is that permanence is unlikely.

2. Issues

2.1. Arsenic Phytotoxicity Issues

conclusions

- Although arsenic solubility is partially lowered by calcium, the light textured slickens soils with high As concentrations will continue to pose phytotoxic risk to plants.

supporting arguments

Arsenic levels in soils typically range from 0.1 to 93 ppm total As (Kabata-Pendias and Pendias, 1992) and are generally less than 15 ppm (NRCC, 1978). The availability of As to plants and the potential for plant toxicity depends on many factors, including soil pH, texture, fertility level, and plant species. Plants tend to have a relatively poor capacity to discriminate arsenate from phosphate. Inorganic arsenate of low solubility makes up the largest fraction of soil As. Arsenate is taken up by the phosphate carrier mechanism. Plants can absorb As through roots and foliage, although translocation is species dependent. Arsenites penetrate the plant cuticle to a greater degree than arsenates (NAS, 1977). Concentrations of As in plants correlate consistently with water extractable soil As, and usually poorly with total soil As (NRCC, 1978). To be absorbed by plants, As compounds must be mobile in the soil solution.

Soil characteristics, especially texture and organic matter content, strongly influence the relative toxicity of As. In general, As is most available to plants in coarse-textured soils having little colloidal material and ion exchange capacity, and is least available in fine-textured soils high in clay, organic material, iron, calcium, and phosphate (NRCC, 1978). For comparison, Kabata-Pendias and Pendias (1992) cite

studies indicating that "in heavy soil, 90% growth reduction appears at 1,000 ppm, in light soil 100 ppm As is equally toxic."

The fate of As is linked to the relative availability of phosphate. Arsenate may be converted to arsenite. In algal systems, under high phosphate conditions, As becomes linked to sulfhydryl residues of protein and becomes toxic. The solubility of As in soils is reduced with increasing alkalinity, organic matter, iron, zinc, and phosphate levels (NRCC, 1978). Kabata-Pendias and Pendias (1992) cite Hanada et al. "Application of materials that produce precipitates of As in soil (e.g., ferrous sulfate, calcium carbonate) is reported to be effective when added to soils having less than 10 ppm of soluble As (in 0.05 N HCl)." Arsenic is reversibly fixed to Ca, becoming available as oxidation conditions change. Arsenic toxicity can persist in soil for several years (Woolson, 1975). The phytotoxic actions of inorganic and organic arsenicals are different, and each is significantly modified by physical processes. An early indication of plant injury by sodium arsenite is wilting caused by rapid loss of turgor (internal water pressure), whereas stress caused by sodium arsenate does not involve rapid loss of turgor (NAS, 1977). Arsenite acts primarily by inhibiting light activation, probably through interference with the pentose phosphate pathway (Marques and Anderson 1986). Phytotoxicity of organoarsenical herbicides is characterized by chlorosis, cessation of growth, gradual browning, dehydration, and death (NAS, 1977).

Although As is not an essential plant nutrient, small yield increases have been observed at low soil As levels, especially for more tolerant crops such as potatoes, corn, rye, and wheat (Woolson, 1975). However, for most plants, significant depressions in crop yields are evident at soil As concentrations of 3 to 28 mg/l of water soluble As and 25 to 85 ppm of total As (NRCC, 1978). A soil concentration as low as 2 ppm soluble As is considered the threshold level for marked damage to alfalfa and barley, whereas 3.4 to 9.5 ppm soluble As causes "poor condition" of young seedlings (Chapman, 1966). Phytotoxicity in Bermuda grass ranged from 45 to 90 ppm in sand and clay soils, respectively. Alfalfa grew poorly in soils containing only 3.4 to 9.5 ppm when soils were acidic, lightly textured, low in phosphorus and aluminum, high in iron and calcium, or contained excess moisture (Woolson, 1975)

Arsenic tolerance results from an adaptation of the phosphate uptake system including competitive interactions between phosphate and arsenate that reduces uptake of arsenate in tolerant plants (Merry et al., 1986; De Koe and Jaques, 1993). In addition, detoxification mechanisms operate in root cells. Flooding and drainage greatly affect As chemistry and availability for plant uptake (Marin et al., 1992). Reduction of As(V) to As(III) upon flooding of soils leads to increased solubility of As. Draining and drying of soil promotes oxidation to As(V), generally thought to be a less toxic form. Soil saturating conditions therefore pose the highest risk of As toxicity. With an increase in pH, hydroxyl ions displace As from sorption sites leading to higher soil solution concentrations(Marin et al., 1993). Merry et al. (1986a, b), concluded that whereas lime application was effective in decreasing the copper and lead content of plants, eliminating arsenic toxicity may require longer term processes such as leaching or microbially-mediated losses to the atmosphere.

2.2. Metals Bioavailability and Nutrient Cycling

conclusions

- Liming temporarily immobilizes many hazardous metals, however, as neutralizing capacity declines, the metals again become bioavailable.

- High rates of liming are known to reduce plant growth.

- Root growth in lime-treated acid soils is restricted to neutralized "pockets" and excluded from poorly mixed zones. This results in added interference among plants reducing productivity and increasing surface erosion.

- High density root growth and associated acid generation by the roots in the neutralized "pockets" can result in increased mobilization of metals in adjacent poorly mixed and unmixed soil zones.

- Nutrient cycling processes are disrupted by liming.

supporting arguments

Availability of metals is strongly linked to pH. Laboratory experiments designed to measure metal release into solution show distinct threshold pH values that differ by metal (Sanders et al., 1986). Aqueous solution concentrations increased sharply as pH was decreased below a threshold value of 6.1 for Zn and 4.8 for Cu in soil-sludge mixtures. Soil pH had little effect on the EDTA extractable concentrations of any of the metals, but had some effect on the concentrations extracted with DTPA.

Apart from the physical-chemical relationships in soil, nutrient cycling is intimately dependent on soil microorganisms. Fungi can function at lower pH conditions than most bacteria. As soil pH approaches neutrality, a broad spectrum of soil bacteria become active. These bacteria form close associations with higher plants in the rhizosphere in a mutualistic manner. The bacteria require organic molecules as sources of energy (these are exuded from plant roots) and the plants benefit from bacterial metabolism that ward off pathogens, mineralize essential nutrients, and buffer the soil zone surrounding roots.

As root growth penetrates into unfavorable soil conditions, including acidic pockets or toxic zones, the associative bacteria do poorly. In turn, the root also does poorly, to the point of die-back. Plant roots commonly exude protons resulting in a slight acidification of the rhizosphere. To the extent that plants and bacteria acidify soil, repeated applications of lime are required in some agricultural settings. The interaction of plants and the physio-chemical processes that promote acid generation, pose serious concerns regarding the long-term effectiveness of lime additions. Whenever, the neutralization balance is lost (even on a micro-habitat scale), nutrient availability for plant growth will decline. Unlimed "pockets" of slickens effectively reduces the soil volume available for plant root growth and increases the magnitude of interference among plants in the favorable, limed microsites. The interference, in turn, reduces the fitness of plants and resulting in lower cover and greater tendency for surface erosion.

Negative plant yield responses to liming often occur on strongly acid, leached soils of temperate areas (Davis , 1981; Lawther and Adams, 1970 as cited in Carran 1991). Reduced availability of P, Mg, and Zn was noted when acid, highly weathered soils were limed (Carran 1991). This was attributed to the formation of new surfaces of hydroxy-Al as pH is raised. The experiments demonstrated that excessive levels of Ca resulting from application of calcareous limestone can damage white clover growth. The damage was in addition to that caused by induced deficiencies of minor element. The negative yield responses to lime on soils that are weakly to moderately weathered and in the pH range 5-6 may be the result of a Ca-Mg imbalance.

Dent (1992) noted that conventionally, acid mine spoil has been reclaimed by liming. Determination of lime requirement must take account of reserves of acid-generating minerals, however the uneven distribution of pyrite within spoil makes reliable control difficult without gross over-liming of the whole deposit. Even though liming can temporarily lower the availability of hazardous metals, the metals remain in the soil profile. As the neutralizing capacity of lime declines and acid conditions return, the metals will once again become available to plants and microorganisms and be mobilized into groundwater sources.

Several problems associated with long term effects of liming to mitigate acidity in forests lead Germany to discontinue the liming practices in the 1970s (Huettl and Zoettl, 1991). Analysis of older liming trials indicated that liming generally leads to a long-term decrease of soil acidity, improvement of cation exchange capacity, base saturation, content of exchangeable Ca (when dolomite is used, also of Mg) and Ca/Al (Mg/Al) ratio. However, an increase of forest productivity due to a faster turnover of organic matter, was not achieved. Enhanced NO_3 leaching leading to loss of soil N of limed soils losses may be significant. Furthermore, it was found that liming can cause acidification of the subsoil (probably due to acids released by roots) and the displacement of heavy metal ions. Liming stimulated fine root development in the uppermost soil layers resulting in increased frost and drought damage. According to (Ulrich, 1972; Evers, 1976 as cited in Huettl and Zoettl 1991) liming practices came to a halt in the mid-

1970s because expectations in increased tree growth were not met and critical questions related to the ecological side-effects of liming arose. In particular, it was feared that a too rapid turnover of organic matter would occur, resulting in enhanced production of NO_3 and its displacement into the ground water.

Relatively small concentrations of heavy metals present in the soil are sufficient to kill all of the free-living effective *Rhizobium* added at inoculum rates of 10^7 cells g $soil^{-1}$ or less within 2 months, but that once clover plants were present and root nodules had formed the rhizobia were protected from toxic effects of the heavy metals (Giller et al., 1993). Ineffective nodules on white clover (>50 separate isolations; Giller et al., 1989) formed in metal-contaminated soils from a field experiment were demonstrated to be wholly ineffective in nitrogen fixation in plant infection tests on a N-free nutrient agar. The plasmid profiles of these isolates were all very similar indicating a lack of genetic diversity in the population surviving in high concentrations of heavy metals. Rhizobium which nodulate white clover are clearly unable to survive (or at least unable to remain effective) outside of the protected environment of the root nodule in this soil contaminated with heavy metals.

2.3. Soil Salinity & Osmotic Stress

conclusions

- Additions of large quantities of lime, especially in sandy soils, results in ionic and osmotic stress to plants during dry periods.

supporting arguments

The addition of lime to sandy soils along streamsides results in sharp increases in salinity. The shift from a low calcium to a high calcium environment results in major shifts of solubility of toxic metals and nutrients as described above. Members of buckwheat, goosefoot, and pink families (Polygonaceae, Chenopodiaceae, and Caryophyllaceae) cannot tolerate high concentrations of dissolved calcium (Larcher, 1980; p 183). Salinity comprised of Na, Mg, and Ca, balanced with sulfates and carbonates affect plants through osmotic stress and ionic effects at subcellular levels. The magnitude of osmotic stress is proportional to the molality of dissolved salts. The ability of a plant to acquire water from soil is related to its ability to maintain a lower water potential than their surrounding medium. Salinity lowers the water potential of soil making it more difficult for plants to obtain water. As soil water content decreases during dry periods, the salt content of the pore water will increase. If sufficient soluble salt is available, the water will achieve osmotic levels that preclude uptake by many plants. This in turn leads to closure of stomates, a water conservation adaptation, and subsequent stoppage of photosynthesis. This sequence of events is prone to limit the competitive capability of sensitive plants.

Ionic stress to plants can occur under saline conditions. With high salinity, cellular expansion is slowed (related to water uptake). Ionic effects also reduce the ability of plants to harden, (i.e., withstand low and freezing temperatures).

3. Redente Study

conclusions

- Subjectively sampled soils and one-time, static measures cannot be used to draw comparisons of dynamic soil processes.
- No evidence is provided to support claims of long-term efficacy of STARS.

supporting arguments

In 1994 and 1995, Redente sampled three areas along the Clark Fork River. These included:

1. tailings revegetated on the Governor's Demonstration Project [GP1 and GP2];

2. naturally revegetated tailings south of the Governor's Project; and

3. a control site north of Racetrack Creek.

He identified general methods in Appendix A of his report, however, many aspects of his description are inadequate to permit detailed analysis of the work. For example on page A-1 he states "sample locations were randomly selected in the field." No supportive information was presented to indicate how this was this done or whether the selection was truly random? Since the procedure for selection of sample points determines the validity of interpretations, failure to provide adequate information limits analytical comparisons. If not properly done, the selection of points can compromise conclusions.

The comparative work done in this study relies on a few measures of general microbial populations. The counts of bacterial cells and measured hyphae of fungi do not provide any insight as to the taxonomic or functional structure of the microbial community. The point-in-time measures of N, known to follow a seasonally dynamic cycle, provided a static view of the process. I concur with the comments of Dr. Gannon (18 September 1995 Critique of Redente Report), especially with regard to the inappropriateness of Redente's conclusion of positive trends based on one-time, static measures of carbon and other soil indices. Though Redente study provides some data, his work do not address the fundamental outstanding issues raised concerning the permanence of STARS *vis-à-vis* toxicity and nutrient conditions. Specifically,

- All measures were taken in the upper 15 cm of soil. This is a zone that receives maximum effectiveness relative to lime incorporation. This surface zone plays a very minor role in restricting arsenic and metal contamination of groundwater.

- As with all of the STARS studies, this one suffers from not having adequately characterized the before treatment - after treatment conditions; and not having heterogeneity characterized.

- There is nothing in this study that attests to the permanence of the treatment. What happens after a flood? What happens as the lime is either neutralized or armored and therefore no longer handles the acid generation?

- What dynamic microbial processes are occurring deeper in the soil profile, particularly in the poorly mixed soils?

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COMMENTS ON THE IMPACT OF STARS [RECLAMATION] TECHNOLOGY ON BACTERIAL PYRITE OXIDATION AND OTHER MICROBIAL MECHANISMS IMPORTANT IN METAL MOBILIZATION

Prepared by:

Testifying Expert:

James E. Gannon, Ph.D.
Associate Professor of Environmental Microbiology
Division of Biological Sciences
University of Montana
Missoula, MT 59812

October 18, 1995

Background:

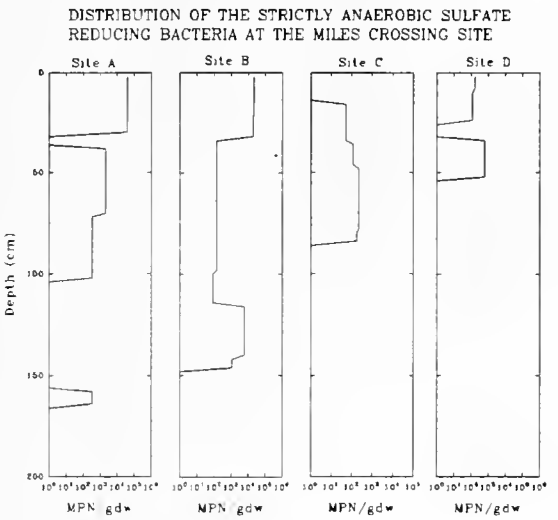
Mine mill wastes deposited in the upper Clark Fork valley contain residual minerals and heavy metals often association with pyrites or metal oxides. Pyrite can be oxidized by specific bacteria found in waste tailings. This oxidation results in the generation of sulfuric acid lowering the pH of the soil and after rain events, the receiving bodies of water become acidic and are highly enriched in toxic dissolved metals. This process is referred to as acid mine drainage. While both abiotic and biotic processes contribute to acid mine drainage, the rate is controlled by the activity of microorganisms. Another potential contributor to leaching of metals into groundwater from waste tailings is the microbial reduction of metal oxides. Due to weathering and other processes much of the tailings material exist as metal oxide complexes. Other heavy metals become associated with these complexes. When metal oxides become reduced, the associated metals are free to migrate into the surrounding aqueous environment. This report addresses the impact of Streambank Tailings and Revegetation Studies (STARS) technology on specific microbial processes critical to acid generation and metal oxide reduction. These processes were not evaluated in STARS research and development and are central to the long-term sustainability of reclamation efforts and protection of surface and ground water.

This report concludes that in amended zones of any tailings deposit, neutralization and vegetation will decrease but not eliminate microbial acid-generation. In thicker tailing deposits, STARS type reclamation is seriously limited in that 1) it fails to reach major zones of acid generating bacteria, and 2) over the long-term, as organic matter accumulates and oxygen tension is lowered, the potential to enhance shallow groundwater contamination is significant.

- *STARS type reclamation will not eliminate acid generation*

Bacterial processes such as acid generation from pyrite oxidation are a product of many factors and not simply pH alone. In lime amended zones, an increase in pH will decrease the activity of the acidophilic iron-oxidizing bacteria and diminish acid generation. It is well known, however, that iron- and sulfur-oxidizing bacteria, as a functional group (i.e. natural consortia), remain capable of acid generation over much broader pH ranges (i.e. pH 2-8) (1,2,4,5). In addition they live in association with other microorganisms including acidophiles (2) and neutrophiles (5) all of which contribute to the acid generation process. In our own research, we have characterized the distribution of acidophilic iron-oxidizing bacteria and neutrophilic sulfur-oxidizing bacteria at the Miles Crossing site adjacent to Silver Bow Creek (see Fig. 2, below). We have found that both groups are widely distributed. This indicates that under a variety of conditions microbial populations capable of acid generation will continue to be active in the tailings profile. These facts have been substantiated by researchers in both laboratory (7) and field studies (14).

FIGURE 1: Vertical distribution of the anaerobic sulfate reducing bacteria at the Miles Crossing Site. Core samples were extracted, fractionated, and analyzed for sulfate-reducing bacteria by MPN enrichment in Postgate C medium.



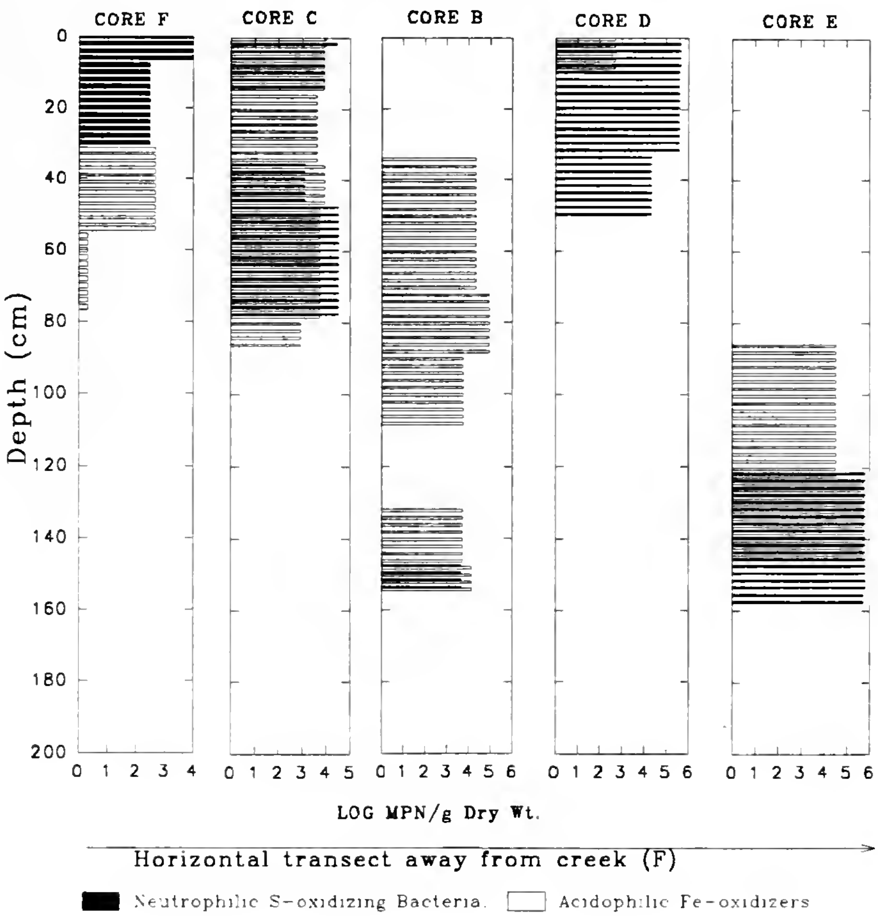
In addition to the microbial diversity, the gross geochemical heterogeneity of tailings is well known. The microheterogeneity is even more immense and one can envision many micro to millimeter areas where amendments are not accessible. These will constitute regions of greater acid-generation. The presence of microscale habitats in tailings is supported by examination of the vertical distribution of the strictly anaerobic sulfate reducing bacteria (Fig. 1). As shown these bacteria are present throughout the profile even where gross geochemical measurements indicate an oxygenated environment. The significance here is that on the scale that lime amendment is to be applied, many microzones populated by acid-generating bacteria will not receive any or not receive sufficient lime treatment and, therefore, zones of high acid generation will exist.

- *Many acid-generating bacteria are found below STARS amendment zones indicating that this treatment is not sufficient in thicker tailings deposits*

Studies conducted in the upper Clark Fork Valley at the Miles Crossing site, demonstrate that the vertical and horizontal distribution of acid generating thiobacilli is quite varied (Fig 2) and in many cases the major zones of acidophilic iron-oxidizing bacteria reside below the area of effective amendment. As reflected in the STARS Phase III Final Report (13) the effectiveness of treatment is restricted to the mixing zone. In Fig. 2 it can be seen that, in thicker tailings deposits, the acid-generating bacteria are found localized at depths up to 160 cm which are well beyond effective treatment. The wide distribution of acidophilic iron-oxidizing bacteria in tailings has been found by others (14).

FIGURE 2: 160 cm core samples, extracted from the Miles Crossing site, were fractionated and analyzed by Most Probable Number (MPN) enrichment for neutrophilic sulfur or acidophilic iron-oxidizing bacteria.

HORIZONTAL AND VERTICAL DISTRIBUTION OF
SULFUR AND IRON OXIDIZING BACTERIA AT MILES CROSSING
SILVER BOW CREEK

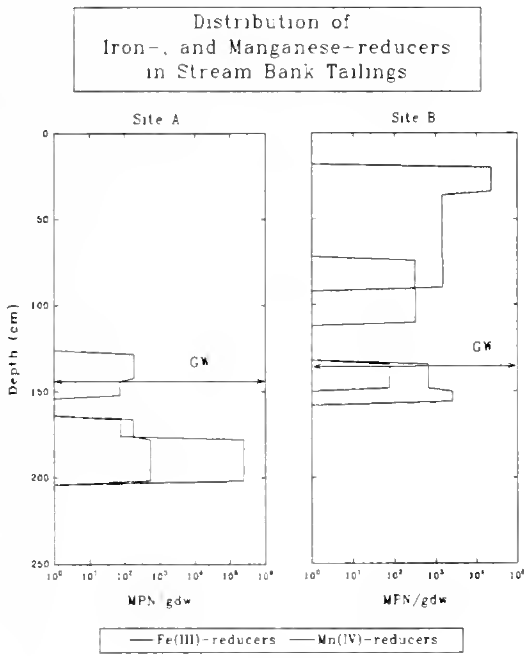


- STARS type treatment has, over the long-term, the potential to enhance shallow groundwater contamination

Due in part to the smelting processes, weathering, and other mechanisms leading to the oxidation of the waste mine tailings, much of the metal contamination in oxic (oxygenated) regions exists as complexes of metal oxides (6). Dissolution of the metal oxides and their heavy metal coprecipitates by abiotic or biotic mechanisms, in effect, remobilize the associated metals. In many suboxic (reduced oxygen) environments microbial metal reduction is considered to be the principal driving force in iron and manganese remobilization (3,10,11,12). Microbial metal reduction plays an important role in the cycling of carbon, trace metals and other nutrients in anaerobic sedimentary environments (8,9,10,12). The activity of iron and manganese reducing bacteria is

governed primarily by pH, community structure, the presence of oxygen, and the availability of organic matter. As oxygen becomes limiting, many nutritionally versatile microorganisms can utilize manganese and iron oxides as terminal electron acceptors provided suitable organic electron donors are available (10,12). Suitable electron donors are often byproducts of other heterotrophic metabolism (fermentation) and include acetate, pyruvate, lactate, formate and ethanol (9). The contribution of these processes to ground water contamination is poorly understood, especially in the tailings environment. We have recently shown that iron and manganese reducing bacteria are prevalent in the tailings environment (see Fig. 3).

FIGURE 3: Vertical distribution of iron and manganese reducing bacteria at the Miles Crossing site. Core samples were extracted and fractionated for analysis of iron and manganese reducing bacteria by MPN enrichment.



Given the concentrations of reducible forms of iron and manganese present in the tailings, these processes could make a substantial contribution to local ground water contamination. Currently, microbial iron/manganese reduction is limited by the existing low pH, low organic matter, and moderate oxygen levels. Neutralization and vegetation will surely increase pH and organic matter, and lower the available oxygen tension. This has a significant potential to enhance microbial metal oxide reduction and remobilize associated metals and metalloids. These processes must be evaluated before long-term sustainability can be ascertained.

This report concludes that in amended zones of any tailings deposit, neutralization and vegetation will decrease but not eliminate microbial acid-generation In thicker tailing deposits, STARS type reclamation is seriously limited in that 1) it fails to reach major zones of acid generating bacteria, and 2) over the long-term, as organic matter accumulates and oxygen tension is lowered, the potential to enhance shallow groundwater contamination is great.

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CHANNEL CHANGE

SILVER BOW CREEK
AND
CLARK FORK RIVER

By

S.A. Schumm

Prepared for

Montana Department of Justice
1310 East Lockey Avenue
Helena, Montana 59620-1425

AYRES
ASSOCIATES
P.O. Box 270460
Fort Collins, Colorado 80527
(970) 223-5556, FAX (970) 223-5578

Ayres Project No. 34-0221.00
SILVER10.TXT

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INTRODUCTION

Alluvial rivers such as Silver Bow Creek and Clark Fork River flow between banks and on a bed of sediment transported by the rivers. They are obviously in marked contrast to rivers that are confined in bedrock or flowing on an armor of coarse sediments, that are no longer transported by the river (Schumm 1977). The channels and floodplains of Silver Bow Creek and Clark Fork River contain tailings that are susceptible to erosion by processes that are characteristic of alluvial rivers such as meander growth and shift and avulsion (**Figure 1**).

An alluvial channel, because it is formed in erodible sediments and because the stress exerted by the flowing water often exceeds the strength of the sediment forming the bed and banks of the channel, will change naturally with time. In Figure 1, six types of natural channel changes are illustrated. Examples A and B are within-channel shifts of bars and islands. In Example B, alternative bars shift slowly downstream, and as they do, the thalweg shifts position. Hence, at one time a bank location is protected by the alternate bar; whereas, at some later time, the bar has shifted downstream, and the bank is subjected to erosion. Example E shows a gradual change of channel position by meander shift. Relatively quick changes by neck or chute cutoffs (C, D) or by diversion (F) are all types of avulsion. Avulsion is a relatively rapid shift of river position in contrast to the slow lateral migration of a river bend. In addition to meander shift (Figure 1E), meanders may also increase in amplitude. This is accomplished by erosion of the cutbank, or the outside of the bend, while sediment is deposited on the inside bank or point bar. Meander cutoffs commonly occur in two different ways: (1) by neck cutoffs, or (2) by chute cutoffs (Figures 1C and D). Both processes shorten the channel, thereby increasing local slope and causing increased scour upstream and deposition downstream.

The continual reworking of sediment demonstrates that the floodplain of a meandering stream is not a permanent feature but is composed of material in temporary storage on its journey downstream. Rates at which the meanders migrate and rework the floodplain depend on many factors. Hickin and Nanson (1975) list discharge, water-surface slope, character of the boundary material, height of the concave bank, bank vegetation, and the ratio of radius of channel curvature to channel width as important in controlling rates of meander migration. Sediment supply to the bend is also important.

Meander migration is inherent to sinuous rivers, and over a period of years, a river will sweep back and forth across its floodplain, reworking floodplain deposits, destroying all surface features, and replacing them with point-bar deposits. Hickin and Nanson (1975) report an average rate of migration of the Beatton River in British Columbia as 0.5 meter per year, during approximately 250 years. The maximum rate during this time was 0.7 meter per year; whereas, the Arkansas River at Bent's Old Fort in Colorado migrated at a rate of 8.0 meters per year during 43 years.

Although rivers are usually described as being straight, meandering, or braided, there is in fact a great range of channel patterns. Straight and meandering channels are described by sinuosity (P), which is the ratio of channel length (L_c) to valley length (L_v), as measured over the same length of valley:

$$P = \frac{L_c}{L_v}$$

For example, a straight channel has a sinuosity of 1.0, whereas a meandering river with a length twice that of the valley has a sinuosity of 2.0.

For simplicity and convenience of discussion, the range of channel patterns can be illustrated by only five patterns (**Figure 2**). These five patterns illustrate the overall range of channel pattern to be expected in nature but do not show the detailed differences within a pattern (Mollard 1973). Nevertheless, Figure 2 is more meaningful than a purely descriptive classification of channels because it is based on cause and effect relations, and it illustrates the differences to be expected when the type of sediment load, flow velocity, and stream power differ among rivers.

In addition to changes illustrated in Figure 1, all of which can be expected during average or bankfull flow, more dramatic changes can occur during high magnitude and low frequency floods. Large floods can cause channel changes from meandering to braided (Figure 2), multiple cutoffs (Figure 1C), channel diversion to another location on the valley floor (Figure 1F), and accelerated meander shift (Figure 1E). Obviously, major floods may not occur for a period of years, but they are inevitable and their impacts can be very significant with regard to erosion and downstream transport of floodplain alluvium, which contains tailings.

Silver Bow Creek

Silver Bow Creek is a low sinuosity (1.2-1.3) stream that wanders across its floodplain. The pattern of Silver Bow Creek varies from straight (Patterns 1 and 2, Figure 2) to slightly sinuous to almost braided (Pattern 4, Figure 2), which suggests that it is in the process of adjusting to the impact of human activities. Tailings from mining and mineral processing facilities in the Butte area occur over about 1,260 acres of the floodplain between Butte and Warm Springs Ponds. A longitudinal profile of the valley (channel elevation plotted against valley distance) reveals that between Butte and the Montana Highway 1 bridge, the valley profile and the creek can be divided into five reaches as follows (**Figure 3**):

1. Butte to Ramsay
2. Ramsay to Durant Canyon
3. Durant Canyon
4. Hot Springs Road to Montana Highway 1
5. Montana Highway 1 to Warm Springs Pond

The five reaches will be described in sequence.

Reach 1. Between Butte and Ramsay, the creek has a low sinuosity, and locally it is confined between two railroads, which prevents major lateral shift (**Figure 4**). The stream gradient is about 0.0035 in this reach, and the valley profile is relatively steep (Figure 3), as compared to the Ramsay-Durant Canyon reach downstream. The creek wanders from north to south across its floodplain in Reach 1. Tailings increase in width downstream from about 100 feet at the junction of Whiskey Gulch to 500 feet at Rocker, as shown on the maps labeled "Intersection of Tailings - Impacted Soil with Ground Water" (Montana State Library 1994). On these eight maps, Silver Bow Creek is divided into four subareas. Hereafter, these maps will be referred to as the Subarea Maps. These maps show that in several places the channel has avulsed. Linear thick deposits of tailings-impacted soil, which are former channel positions, lie to the north and south of the present channel near Rocker and at several locations upstream of Nissler (**Figure 5**). These remnants of former channels appear to be evidence of avulsive change (Figure 1F) because the thick sedimentary deposits are separated from the present channel by thin deposits. Hence, the channel apparently did not move progressively from the old to the new channel position; it avulsed.

Although sinuosity is low, Silver Bow Creek wanders from north to south across the area of tailings in Subarea 1, and it is logical to conclude that this wandering will continue in this steep reach, although as noted above, the channel change can be avulsive (Figure 1F) or the channel may become more sinuous.

For example, the presence of cobbles and boulders in Reaches 3 and 4 suggest that they also exist beneath the tailings in Reaches 1 and 2. If an armor of cobbles and boulders develops in this reach, the channel could meander on the armor. The channel would shift across the armor and erode the tailings, which is occurring at present bends (**Figure 6**). In many mountain parks and valleys, channels are highly sinuous. This is because, although the banks are erodible, the bed is not. Cobbles and boulders that were deposited under previous different discharge conditions form an armor over which the modern channel shifts and forms meanders. In fact, downstream of Nissler and upstream of Ramsay, the channel is slightly more sinuous in 1990 than it was in 1955, which suggests that there is a tendency for Silver Bow Creek in Reach 1 to meander.

Reach 2. Between Ramsay and Durant Canyon the valley profile flattens abruptly (Figure 3), channel gradient decreases to about 0.002 and the width of the tailings increases to about 1,300 feet (**Figure 7**). There is a constriction just downstream of Browns Gulch where bedrock is exposed on the south side of the creek (**Figure 8**). The marked flattening of gradient in Reach 2 may be the result of bedrock beneath the channel at this location. The reduced gradient has resulted in a substantial accumulation of tailings in this reach. As in Reach 1, Silver Bow Creek wanders across the tailings, and traces of previous channel positions indicate avulsive change of channel position. Upstream of Miles Crossing (**Figure 9**), there are several abandoned segments of Silver Bow Creek. Two of these contained water in 1955, but not in 1990. Therefore, complete abandonment of these segments occurred after 1955. As in Reach 1, the channel is slightly more sinuous in 1990 than it was in 1955. This probably reflects channel adjustment to reduced sediment loads, and it may be an indication that instead of the avulsive change of the past, the channel will develop a more sinuous course with bank erosion becoming the primary mode of channel change (Figure 8). Large floods will accelerate the process and mobilize tailings stored in the floodplain.

Reach 3. In Durant Canyon, the creek is confined by canyon walls and the railroad grade in a steep reach that has a gradient of 0.006 (Figure 3). The bed, where visited in this reach, is composed of cobbles and boulders. Locally, the valley widens, and tailings have spread across the valley floor. At these locations, channel shift can cause erosion of the tailings. Major floods can flush stored sediment and tailings from this steep narrow reach to Reach 4.

Reach 4. Downstream of the Fairmont Hot Springs Road, the tailings have been deposited across a 3,000-feet wide floodplain between Crackerville and Montana Highway 1. Although the creek has left the canyon (Figure 3), the bed is composed of cobbles and boulders, and channel gradient remains very steep (0.006). The downstream convexity of the contours on Subarea Maps 7 and 8 (Montana State Library 1994) indicate that in cross section, this reach is broadly convex. Therefore, it is similar to an alluvial fan. Aerial photographs and subarea maps show many abandoned channels in this reach, which indicates that the channel frequently avulsed across the fan (**Figure 10**). Locally the channel has been straightened and confined by levees (**Figure 11**). Elsewhere, the creek can apparently avulse to almost any location on the fan, and it can meander on the cobble-boulder armor. Both processes will result in erosion of tailings in Reach 4.

Reach 5. In the short reach between Montana Highway 1 and Warm Springs Pond, both valley slope and channel gradient decrease, sinuosity increases, and the width of the tailings decreases markedly. The downstream concavity of the contours on the Subarea Map indicates that the cross section is no longer convex. This short reach could be included in Reach 4, but the differences may be important. Indeed, the channel pattern in Reach 4 may resemble the original Silver Bow Creek pattern. For example, sinuosity is about 1.6 where the channel has not been straightened. This suggests that a similar high sinuosity meandering channel could develop in Reaches 1, 2, and 4.

Clark Fork River

The upper Clark Fork River between Warm Springs Creek and Garrison is meandering, and it is relatively sinuous (2.0), but the gradient is significantly less than Silver Bow Creek in Reaches 3 and 4 (0.003). The bed of the river is composed of boulders, cobbles, and

gravel. The river actively forms and cuts off meanders (**Figure 12**), and aerial photographs permit identification of numerous recent cutoffs (**Table 1, Figures 13, 14**). Similar changes can occur anywhere between Warm Springs Creek and Garrison, and tailings stored on the floodplain or in cutoffs will be remobilized by this type of channel change.

Table 1. Location of Cutoffs, Clark Fork River South of Deer Lodge.

Location	Approximate Distance of Channel Shift (ft)
Warm Springs Quadrangle	
T5N, R9W, NE1/4 Section 7	200
T6N, R9W, Center Section 32	600
Racetrack Quadrangle	
T6N, R9W SE1/4 Section 20	800
Orofino Creek Quadrangle	
T6N, R9W SW1/4 Section 16 (2 cutoffs)	300, 200
T6N R9W NE1/4 Section 16 (3 cutoffs)	200 maximum
T6N R9W E1/2 Section 9	1,000
T7N, R9W NW1/4 Section 21 (2 cutoffs)	1,400, 200
T7N R9W SW1/4 Section 16	1,200
T7N R9W N1/2 Section 16, SW 1/4 Section 9	1,900

CONCLUSIONS

Field observations and study of maps and aerial photographs indicate that Silver Bow Creek will erode the tailings, as the channel wanders across its valley floor, develops meanders, or when it avulses across the tailings. Avulsive change in the recent past suggests that the creek can shift abruptly to a new position, especially in Reach 4. Numerous cutoffs along Clark Fork River between Warm Springs and Garrison indicate that avulsive change as well as meander growth and meander shift are continuing. All of these changes will result in erosion of tailings. The possible development of a meandering channel in Reaches 1, 2, and 4, that would be similar to the sinuous channel in Reach 5, will cause significant erosion of floodplain alluvium. Large infrequent floods will, of course, accelerate the process.

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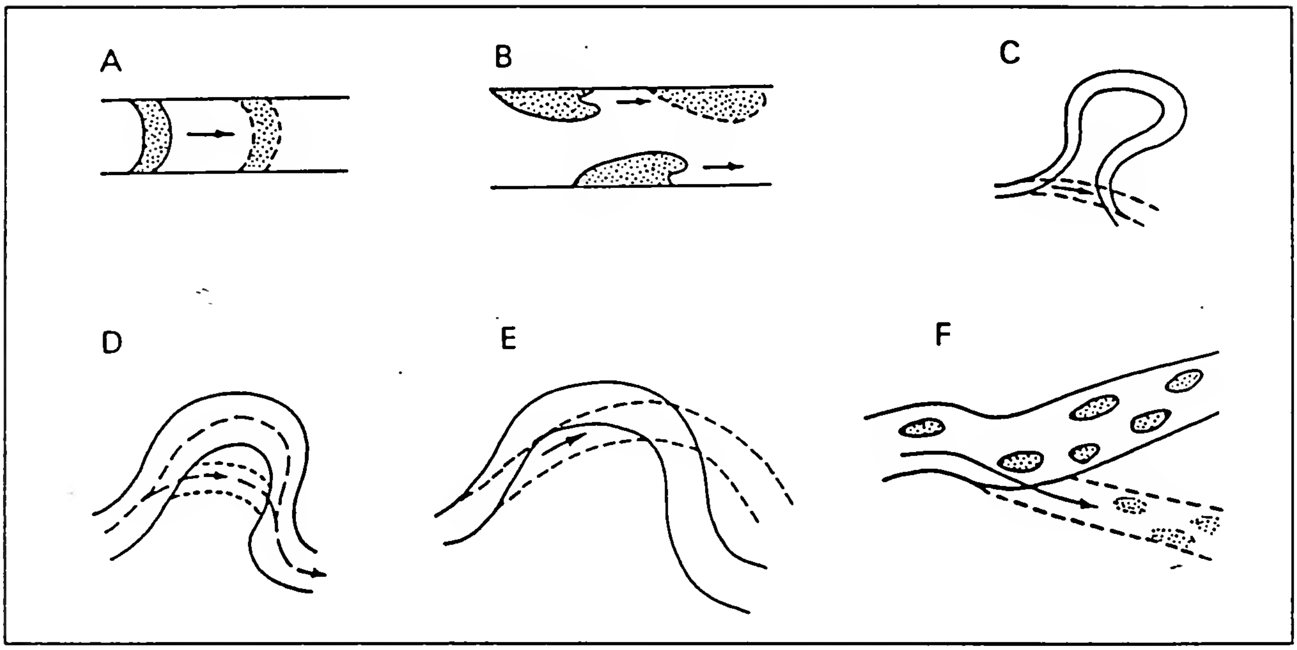


Figure 1. Types of channel changes: A. transverse bar shift; B. alternate bar shift; C. neck cutoff; D. chute cutoff; E. meander shift; F. diversion. Full lines indicate present status and broken lines the future potential changes (from Shen and Schumm 1981). Examples C, D, and F are types of avulsion.

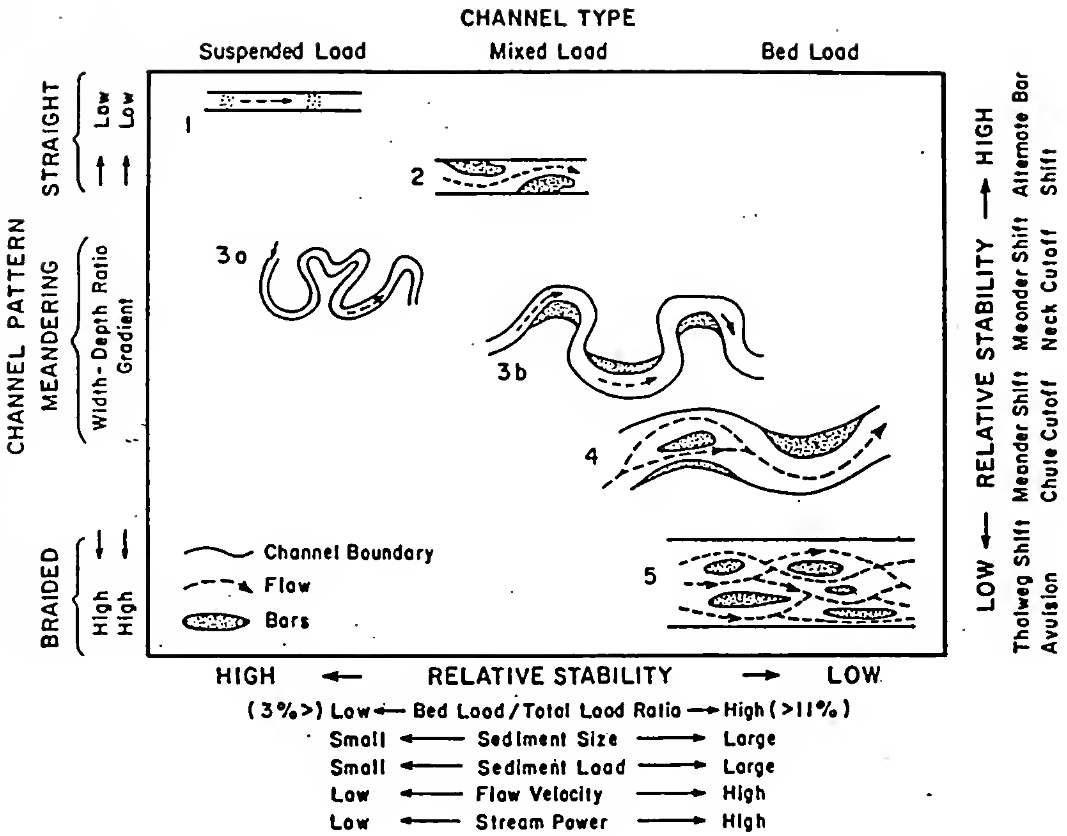


Figure 2. Channel classification based on pattern and type of sediment load with associated variables and relative stability indicated.

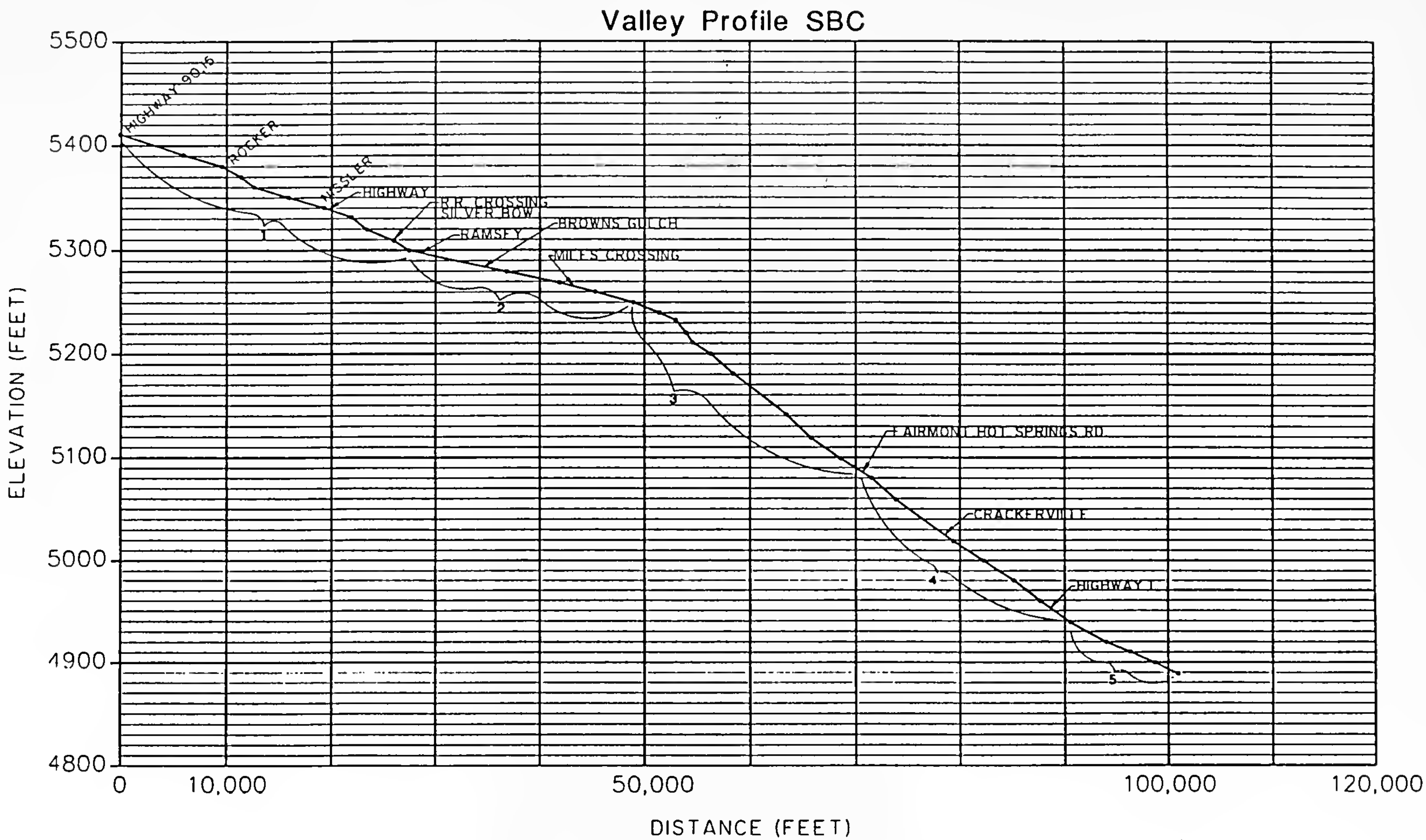
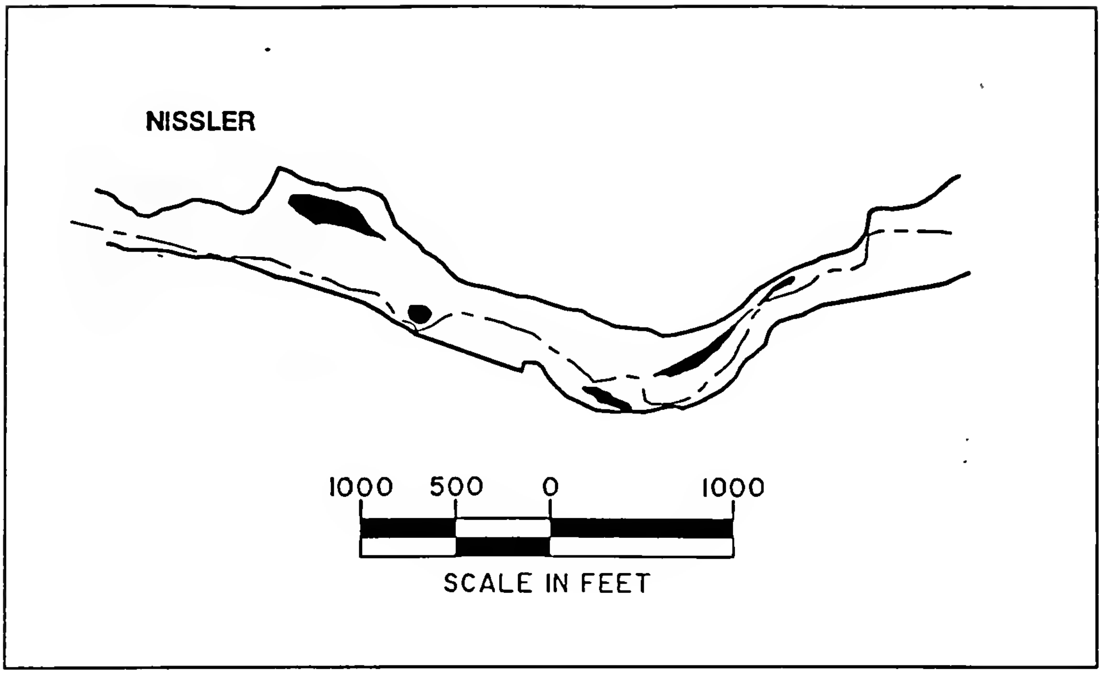


Figure 3. Valley profile of Silver Bow Creek showing 5 reaches, as described in text.

Figure 4 Silver Bow Creek confined between railroads near Nissler.



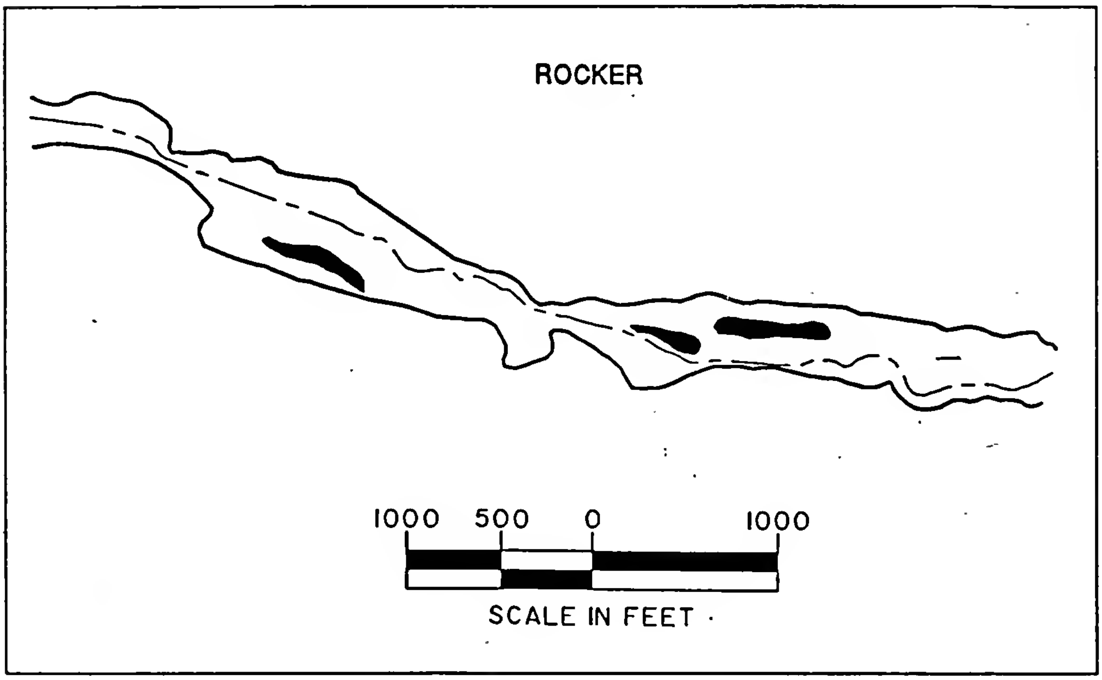


Figure 5. Former channel positions near Nissler and Rocker. Two outer lines show extent of tailings. Inner broken line is position of Silver Bow Creek. Dark areas are thick tailings, which are former channel positions. Downstream is to the left.

Figure 6. Erosion of tailings near Ramsay

Figure 7. Tailings, Ramsay Flat.

Figure 8 Bedrock hill on left bank of Silver Bow Creek near Browns Creek junction.

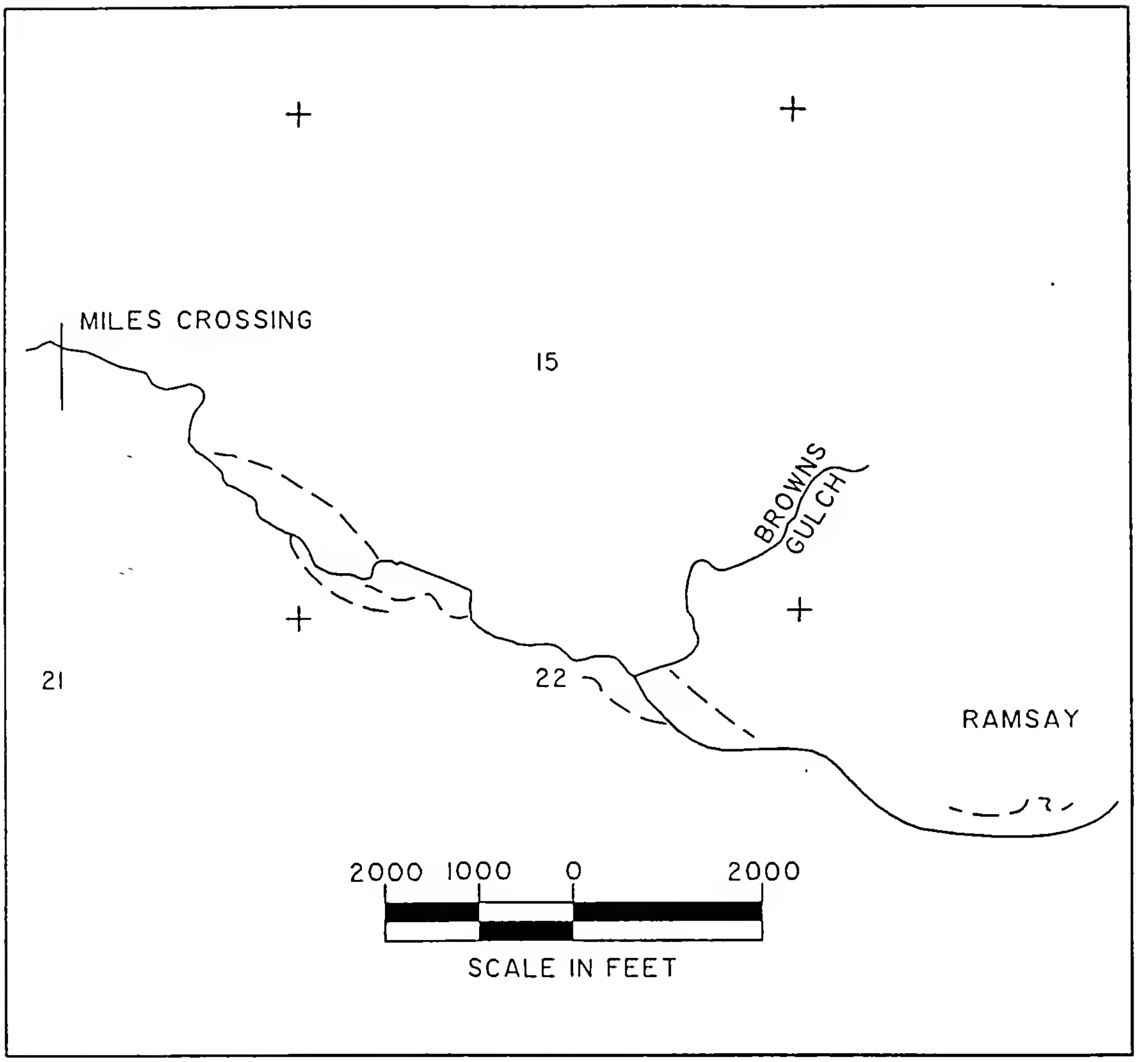


Figure 9. Silver Bow Creek channel changes, Ramsay quadrangle. Solid line shows approximate location of Silver Bow Creek in 1990 and dashed line shows former position of creek as identified on 1954 and 1955 aerial photography. Crosses show location of section corners and numbers identify sections. Downstream is to the left.

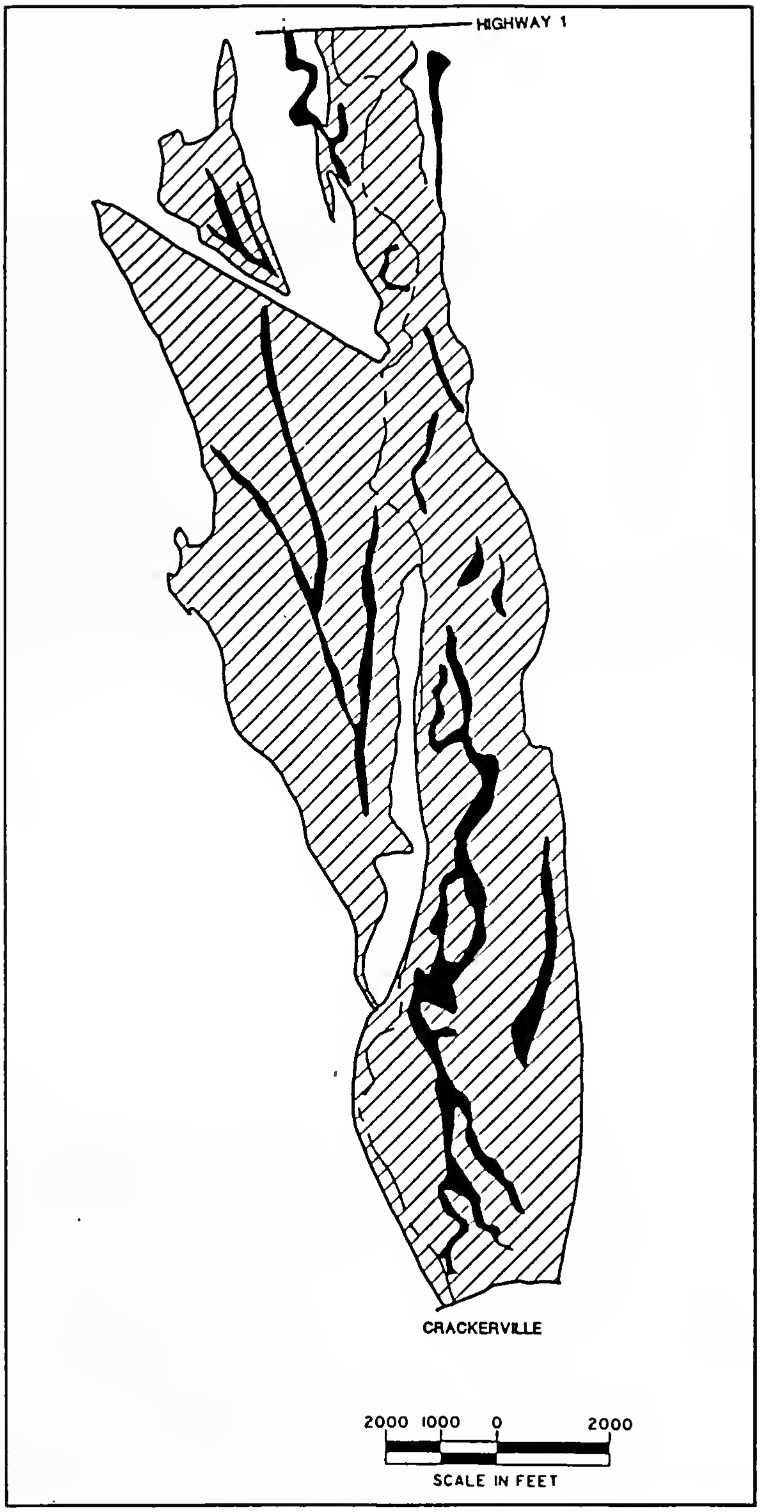


Figure 10. Some former positions of Silver Bow Creek between Crackerville and Montana Highway 1. Solid lines and pattern indicate extent of tailings; broken line is position of Silver Bow Creek. Black areas are former channel positions, as based on subarea maps and 1955 aerial photography.

Figure 11. Silver Bow Creek in Reach 4. View downstream from channelized and leveed portion of channel toward bend and low banks of natural channel.

Figure 12. Meander cutoff, Clark Fork River, upstream of Galen Road

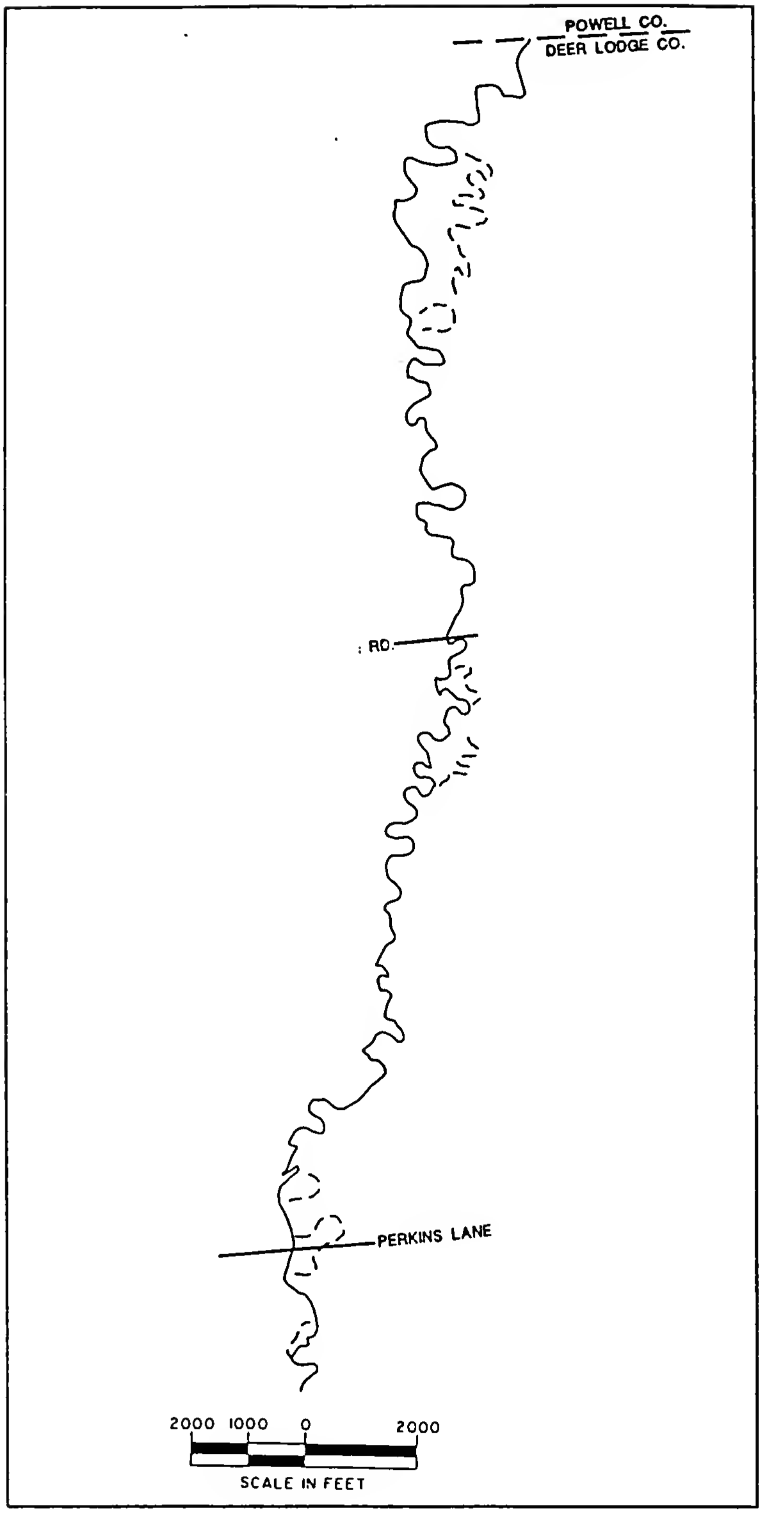


Figure 13. Clark Fork River channel change from south of Perkins Lane to county line. Dashed lines show former channel positions as based on aerial photographs and Warm Springs, Racetrack, and Orofino Creek quadrangles. Downstream is toward top of figure.

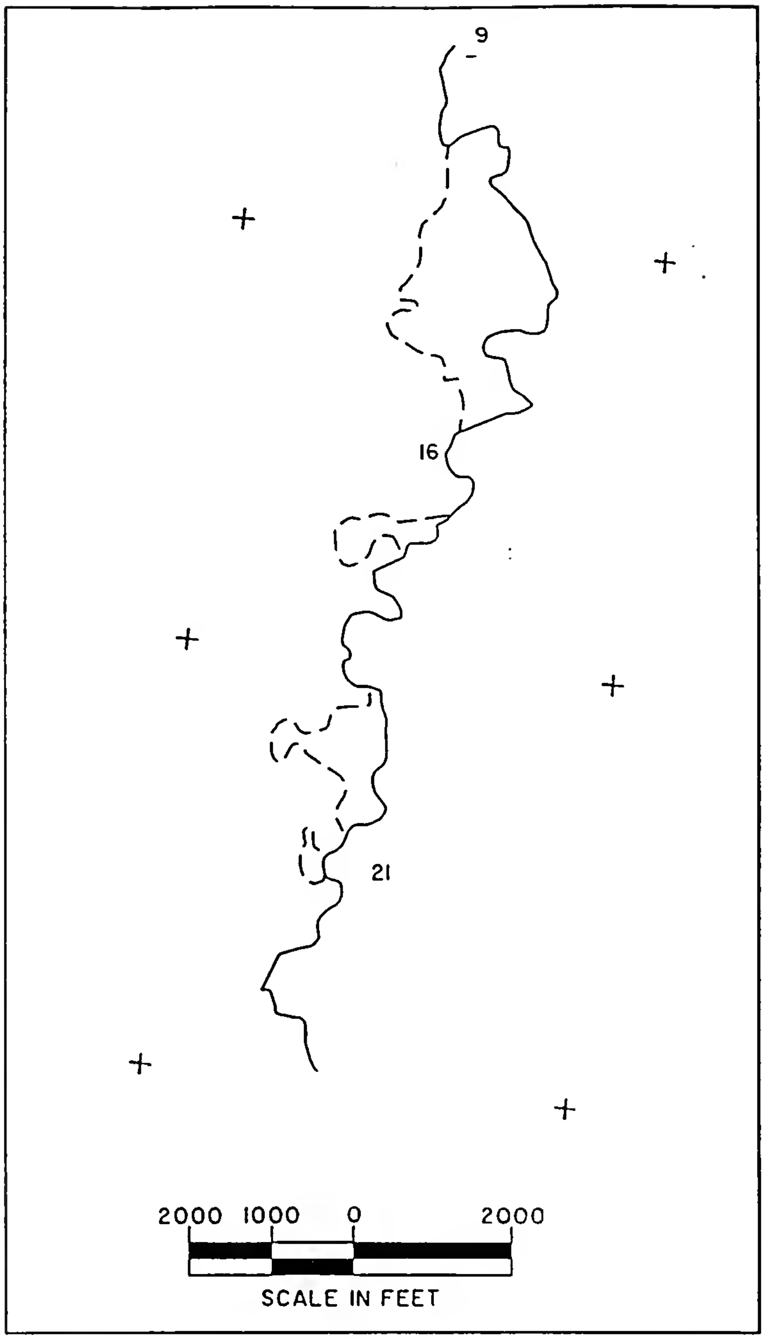


Figure 14. Clark Fork River channel change south of Deer Lodge, which is one mile above top of figure, Orofino Creek quadrangle. Downstream is toward top of figure. Solid line shows location of Clark Fork River. Dashed line shows former location of channel. Crosses are section corners, and numbers identify sections. Both the Clark Fork channel and cutoff channels contained water in 1955; therefore, the cutoffs commenced earlier than 1955, and they still appeared to convey some flow in 1990.

COMMENTS ON ARCO'S REPORTS CONCERNING THE REVEGETATION OF ACID TAILINGS NEAR COOKE CITY, MT; THE IDARADO MINE, CO; AND ON WHITEWOOD CREEK, SD.

Prepared by:
Eugene E. Farmer

Testifying Expert:

Eugene E. Farmer, Ph.D.
Farmer and Associates, L.L.C.
P.O. Box 204
Providence, Utah 84332

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REVEGETATION OF ACID TAILINGS

Tailings Revegetation

Revegetation of tailings can be an extraordinarily difficult undertaking if the plant roots have to establish themselves in the tailings material. Tailings are often extremely acid and have large potential acidity. Tailings are often toxic to vegetation due to this acidity and high concentrations of soluble heavy metals. Tailings normally have low water holding capacities, and frequently have high specific conductivities, i.e., they are salty. Further, they lack common plant nutrients, possess low soil cation exchange capacities, and cannot recycle plant nutrients because soil exchange sites are saturated with salts and heavy metals and required nitrifying fungi and bacteria are absent. Finally, they have high unit weights, i.e., the tailings are heavy and tightly compacted, and present physical difficulties to root penetration. All of these factors have to be overcome in order to establish a satisfactory stand of vegetation. If the aim of the revegetation is a permanent, self repairing stand of vegetation adapted to the site, then the stand must persist long enough for natural plant succession to achieve a mix of adapted plant species. I am not aware of any successful examples of tailings revegetation where a permanent stand of desirable vegetation has been established directly on tailings for a period of 10 to 15 years without the periodic input of lime, plant nutrients, seed, or organic materials.

There is also a widespread misunderstanding regarding the revegetation of acid tailings. There is the impression that successful vegetative reclamation of sulfide bearing tailings material will stop the flow of contaminated water from those tailings. The belief persists that a heavy stand of grass, forbs, or other vegetation will somehow stop the oxidation of sulfides and stop the further generation of acid by protecting the surface of the tailings material from erosion that would otherwise expose new sulfide minerals to the atmosphere and renewed oxidation. These are false hopes, at least in any reasonable time frame. I am unaware of any literature for the western United States where data has been published that demonstrates an effective improvement in the water quality draining from sulfide mineral tailings as a result of revegetation. Revegetation, and all that it implies, does not stop the oxidation of sulfide minerals and the resulting formation of sulfuric acid (Farmer and Richardson, 1981).

In spite of the fact that revegetation of acidic tailings has little or no effect on the rate of acid formation, or on the quality of acid drainage, a large amount of research effort has been expended toward revegetation. There is an important role for a cost effective vegetal cover. Barth (1986) lists several important effects of a good vegetal cover. First and foremost, vegetation offers an effective means of controlling wind and water erosion. This affects the stability of the tailings proper and can be especially important near populated areas. Vegetation also transpires large quantities of water, thereby reducing water infiltration and drainage in the impoundment. Last, vegetation is aesthetically appealing and can reduce adverse visual impacts.

One of the key factors in the revegetation of acid mine tailings is the proper and appropriate use of liming materials. Inaccurate methods for the determination of the amount of lime to apply, and insufficient sampling methods have often resulted in failure. There is not widespread agreement on the appropriate method of calculating the amount of lime that is required for a given tailings. Sometimes the calculated amount of lime to neutralize the total potential acidity is so great that it is physically impossible to apply that much lime in an effective, efficient manner.

Periodic reliming is one way of dealing with tailings reacidification. But reliming over an existing stand of vegetation can be disruptive to vegetal development. Finally, due to cost or other factors, the wrong liming agents may be used, or the proper lime agents are used inappropriately. In many instances in the last 25 years reclamationists didn't know exactly how to calculate lime requirements for a given situation. In some cases lime was used to neutralize the surface, only to find that oxidation of residual pyrites, and the upward migration of acids by capillary action killed all of the vegetation. In one of the earliest efforts to revegetate acid tailings, Nielson and Peterson (1972) applied 60 tons per acre of crushed limestone to a copper tailings pond in Utah only to have the treated area reacidify in less than one year. Subsequent field work showed the total potential acidity to be greater than 100 tons of limestone per acre. This work was valuable to reclamationists since it was one of the first documented cases of lime requirements on acid tailings ponds.

McLaren Mine Tailings, Montana

In his expert report to the Atlantic Richfield Company , dated July 10, 1995, Dr. Thomas C. Ginn delivered a commentary on the issue of tailings revegetation, including liming. As supporting argument to his discussion of STARS issues Dr. Ginn suggests other sites around the western United States as examples of successful revegetation; one of these sites is near Cooke City, Montana. I believe that Dr. Ginn overstates the case when he says that . *"...revegetation of mine tailings at a site near Cooke City, Montana, has thrived for more than 17 years (sic).*" It is uncertain which site or sites Dr. Ginn references. It might be the McLaren tailings impoundment just outside of Cooke City, MT, or it might be one or more of the revegetation trials conducted on sites near the McLaren and Glengarry Mines. These mines are about 10 miles from of Cooke City. I will address the tailings impoundment at Cooke City and then the revegetation research at the McLaren and Glengarry Mines.

The Tailings at Cooke City, Montana

Ore from the McLaren Mine, part of the New World Mining District, was processed primarily for gold and silver (and occasionally for copper) from approximately 1905 until 1953, using a cyanide leaching process (EPA Fact Sheet, 1989). This ore was processed at a mill near Cooke City, Montana. About 150,000 cubic yards of tailings were deposited in and adjacent to Soda Butte Creek, which runs through Cooke City. While the tailings waste contains hazardous substances, arsenic, copper, lead, and zinc, the concentrations are not high and the tailings were never particularly acid. Typical metal contents in the dry tailings matrix are approximately as follows: arsenic, 4 to 45 mg/kg; lead, 55 to 208

mg/kg; copper, 103 to 3680 mg/kg; and zinc, 81 to 102 mg/kg. EPA determined that the tailings do not pose a human health threat, but do pose significant environmental impacts. Fish and the benthic organisms that support them are susceptible to metal ion toxicity, especially copper. Tailings pH is reported by EPA as ranging from 2.3 to 7.4 in the tailings material proper, and from 3.7 to 7.5 in seepage draining from the impoundment. In 1987, the average pH in Soda Butte Creek above and below the impoundment was 7.5 and 7.8, respectively. This indicates that little or no acidity is leaving the impoundment. In general, the tailings may show occasional pockets of strong acidity, as noted by a pH of 2.3. But, over most of the impoundment the pH values are much higher, probably averaging more than 5.0. Seepage from the impoundment draining into Soda Butte Creek may be somewhat acidic, but not strongly so. Soda Butte Creek is generally not acidic. However, yellow-boy (ferric hydroxide) is present at the impoundment seepage outflow. These indications of weak acidity also correspond with the fact that much of the McLaren Mine ore was processed by cyanide extraction methods. This indicates that the ores were probably oxide ores, not sulfide ores; sulfides are not amenable to cyanide processing. Oxide ores normally produce only minor amounts of acidity, or none at all.

It is difficult to know, or even guess, what Dr. Ginn had in mind if he addressed this site as an example of tailings revegetation that has thrived for 17 years. In the 1960s the Bear Creek Mining Company did spread some nearby glacial till soils over the tailings. Portions of the area have been limed and reseeded at least twice since then. My personal observations are that the site supports a sparse stand of grasses. Lodgepole pine and a few shrubs have occasionally invaded the border area. However, it is not clear that these trees and shrubs are rooted in tailings since the tailings are thin in the border areas. The tailings at Cooke City are not a good example of long-term tailings revegetation success.

Overburden Waste at the McLaren Mine

It seems more likely that Dr. Ginn's remarks about revegetation of mine tailings and vegetation that has thrived for more than 17 years were addressing the research work conducted by Dr. Ray Brown of the U.S. Forest Service at the McLaren and Glengarry mines. Dr. Brown, myself, and other scientists started this work at the McLaren mine in 1972. Dr. Brown has been active on the site since that date.

If Dr. Ginn's intent was to address the revegetation success at the McLaren Mine as exemplary of the success possible on the Silver Bow Creek tailings, he is in error. There is not, and never has been, a mill at the McLaren Mine, hence there are no tailings at the McLaren Mine. Dr. Brown's revegetation work has been confined to overburden waste. Tailings are a more difficult medium for revegetation than is overburden waste. The principal direction of Dr. Brown's research has been to discover revegetation techniques and adapted plant materials for high elevation and alpine disturbances. The McLaren Mine is about 9000 feet elevation. Neutralization of overburden acidity is more a nuisance factor than a major thrust of his research. And while some of the overburden wastes at the McLaren Mine are acid, most have a low potential acidity. It is possible to neutralize the entire acid potential within the root zone with a single lime application. Liming rates

suggested by Dr. Brown for revegetation on these sites range from 2 to 10 tons of lime per acre. Compare this with acid potential values ranging up to 233 tons per acre for tailings along portions of Silver Bow Creek. These sites are not comparable.

Tailings Reclamation at the Idarado Mine, Colorado

I have not personally seen this site. My knowledge of the site is based on telephone conversations with the On Scene Coordinator for the Colorado Department of Health and the documents that she has sent to me. However, I have been in the vicinity of this mine, around Ouray and Telluride, Colorado, many times and have general knowledge of the mining in the area.

In his expert report for ARCO, Dr. Edward F. Redente cites the successes achieved at the Idarado Mine tailings as comparable to STARS technology, and further, as supporting evidence that STARS type technology will produce self sustaining plant communities. Dr. Thomas C. Ginn also references the Idarado Mine as a good example of tailings revegetation success. As at the McLaren Mine tailings, I believe that these scientists are overstating their case. Moreover, I feel that they are also drawing unwarranted comparisons between vastly different sites and vastly different reclamation proposals.

Tailings reclamation work at the Idarado mine has little long-term history, since most of this tailings reclamation work has been conducted since 1986. It is not clear that reclamation work in the 1980s on these sites has resulted in self perpetuating stands of vegetation since they have been the recipient of on-going management inputs of lime, seed, and fertilizer. In addition, 10 additional tailings piles were scheduled for new reclamation work starting in 1993, in a phased approach (Remedial Action Plan) negotiated between the mining company and the State of Colorado.

In general, the tailings materials at Idarado are not strongly acid, so an intensive revegetation effort is more likely to succeed than on strongly acid tailings. As in other tailings materials there is a lot of variability in the tailings between piles, and with depth in the same pile. Metal ions are abundant in these tailings but not in surprising quantities or concentration. The principal metals in the tailings are lead, manganese, copper, and zinc. There are lesser amounts of silver and cadmium. Seepage from the piles will be controlled by concrete drainage ditches, but controls on the ditch drainage seem minimal. In some cases the ditch drainage will be treated in a passive manner, probably with a wetland treatment system. This is not indicative of strongly acid, metal contaminated, pond drainage.

The work that was begun in 1993 follows the pattern that was negotiated in the Remedial Action Plan. The surface of the tailings are quickly brought to pH 7 with quicklime. This requires only 1 to 5 tons per acre. The rest of the revegetation procedures that are implemented are of heroic proportions: 30 tons/ac of pea size limestone tilled into the surface, 40 tons/ac of dry manure tilled into the surface, 20 tons/ac of straw or hay worked into the surface to increase the organic matter content, fertilizer is applied at the

rate of 50 pounds of nitrogen per acre, 250 pounds of phosphorus per acre, and 80 pounds of potassium per acre, along with 42 pounds per acre of pure live seed (grasses and forbs) followed up with an application of 2 tons/ac of straw mulch. No coversoil is used.

Following this initial revegetation effort there will be a 5 year establishment period where the Idarado Mine is allowed considerable latitude to irrigate the seeding, or to make other management inputs into the effort, lime, seed, fertilizer, in order to insure success. Following the establishment period there will be a 10 year evaluation period where further inputs to the revegetation effort are prohibited. If vegetation failures occur, coversoil may be required at depths of 18 inches or greater.

Clearly, statements indicating that the Idarado tailings trials have resulted in desirable plant communities that are self sustaining are hopelessly premature.

Tailings Along Whitewood Creek, South Dakota

I have not personally visited the superfund site along Whitewood Creek, South Dakota. The following remarks are based on my review of the Record of Decision for the site, issued by the EPA on March 30, 1990, on the draft Preassessment Screen for Natural Resource Damages issued by the State of South Dakota on May 2, 1995, and on information gathered in telephone conversations with personnel of the South Dakota Department of Environment and Natural Resources. The information contained in these documents and conversations has been supplemented by my general knowledge of mining, acid mine drainage, and reclamation.

In his expert report to the Atlantic Richfield Company, dated July 10, 1995, Dr Ginn cited the revegetation success on tailings at a mining superfund site near Whitewood, South Dakota as supporting the long term revegetation effectiveness of STARS techniques developed along Silver Bow Creek, MT. However, these two sites, Silver Bow Creek and Whitewood Creek are not comparable.

The Whitewood Creek Superfund Site is located near the town of Whitewood, and comprises an 18 mile stretch of the creek that includes tailings settled along the creek bed and flood plain that is variously estimated between 21 and 30 million tons of mine tailings. The EPA estimate is 21.6 million tons. The site is located along the lowest segment of the creek, just before it empties into the Belle Fourche River.

The acidifying agents of greatest concern in the tailings are iron and arsenic sulfides; the tailings produce a weak solution of sulfuric acid (EPA, 1990). The potential acidity is mostly neutralized, both by the calcium carbonate in the tailings, and by the limestone formations exposed along the stream course. Most of the contaminant transport in the system is in the solid form of the contaminants, rather than in solution. Throughout the 18 mile length of the site, in all but a few locations, the tailings support stands of vegetation that have naturally invaded the flood plain. The State of South Dakota estimates that 75 per cent of the tailings deposits support vegetation, including grasses, shrubs, and trees.

The vegetal cover that has been naturally established on most of the tailings can probably be attributed to several factors. One strong mitigating factor is that the tailings are neither strongly acidic nor toxic to vegetation. It is also likely that areas of tailings are thinly deposited so that the plant roots have become established in non-tailings materials.

It hardly seems reasonable to suggest, as Dr. Ginn did, that the Whitewood site and Silver Bow Creek are comparable. While Whitewood Creek may have more tailings deposited within its floodplain, they appear to have substantially less capacity to produce acid than Silver Bow Creek. This also accounts for the fact that most of the tailings along Whitewood Creek have established stands of vegetation through natural plant succession, without artificial additions of lime, seed, or fertilizer. This condition is reflected in the EPA Record of Decision that declined to remove the tailings or to revegetate them in place.

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